LEADING INDICATOR ANALYSIS FOR HIGH SPEED SLED TEST PROGRAMS

THESIS

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Abstract

Leading Indicators (LI) were introduced to the Systems Engineering (SE) community in 2007. These measures are used to evaluate the effectiveness of how a specific work activity is applied on a project in a manner that provides information about impacts that are likely to affect the system performance. The LIs are designed to give a project manager/systems engineer insight into where their development project is heading and a chance to implement corrective actions early. This research strives to apply LIs to the testing community, specifically high speed sled testing, to improve the testing process and, in turn, improve the quality of the tests conducted. The thesis captures which SE processes are emphasized, valued and used in the high speed sled test community, then identifies LI trends that are most relevant to the high speed sled test community. Lastly, two of the top LIs - requirements maturity and requirements validation - were chosen for further trend analysis. Both of the LI trends were broken down into their suggested derived measures and current project trends were compared to historical trends.

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I. Introduction

Background

Multiple high speed sled test tracks around the world, such as the Holloman High Speed Test Track (HHSTT), have provided the testing community with a unique way to evaluate systems that will be subjected to a high speed flight environment. On average three sled tests can provide 90 percent of the information at 10 percent of the cost compared to one flight test (9). The systems that have been tested range from penetrator weapons to ejection seats to high-speed rain erosion materials. This thesis will concentrate on the penetrator weapon system tests, which consist of accelerating a test article (Figure 1) to a desired speed and impacting it into a target complex (Figure 2). This type of test is also referred to as an impact test.

Figure 1: HHSTT Sled Train

Figure 2: HHSTT Target Complex

Testing at a high speed sled test track is very unique. Sled tests are one shot tests; no test is identical to another. The typical length of a sled test project, from the first requirement to the project closeout, can range from 5 to 12 months. There is very little room for last minute changes, and the process seeks to remove timely backtracking throughout the engineering activity. Once a test has been launched the entire planning process starts over.

Testing these systems on a high speed sled track helps confirm performance models, reduce cost for late design changes, identify and decrease safety risks, and decrease cost as part of the system development. High speed sled tests have strong similarities to acquisition programs with test requirements, test infrastructure design and development, and test planning and execution. Since each test involves high risks, large costs and a demanding schedule, SE should have a strong role. SE is defined as:

> an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while

> considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (10)

A fairly new SE tool is the SE leading indicator (LI). An LI is a tool used to help predict the outcome of a project within a given confidence and time range, "provide engineering leaders with the information they need to make informed decisions and, where necessary, take preventative or corrective action during the program in a proactive manner." (12) SE and the LI tool play an important role in decreasing risk, cost, and schedule. (12,13)

Problem Statement

"Systems engineering is widely used, but at a relatively low level…" (18) was reported in a survey conducted on systems engineering in aerospace and defense industries. These findings do not differ much in the test community. Portions of the SE processes are used but at relatively low levels. In some cases, such as at the HHSTT, the test community does not actively practice SE, yet unknowingly uses some of the SE processes in their day to day work. One of the reasons SE is being used at relatively low levels is the lack of confidence in the SE process. (18) Not all of the *Defense Acquisition Guide's (DAG)* 16 SE processes (3) or the International Council on Systems Engineering's (INCOSE) 18 SE processes (10) are utilized in the testing environment. When a customer tests their system or payload at a high speed sled track they are interested in conducting a test that satisfies requirements, is low risk, on schedule, and within budget. Applying the use of LI tools to a high speed sled test may help to improve the sled test process and in turn improve the quality of the tests conducted.

Research Focus

The focus of this research effort was to evaluate the potential use of LIs on a high-speed sled test during impact sled test projects. During this research, the following questions were answered by conducting a quantitative study of past and current impact sled tests:

- What SE activities does the high speed sled track community currently emphasize, value and use?
- Which of the 18 LI trends are most relevant to a high speed sled track environment?
- How do the current project trend lines compare to the historical trend lines for different LI trends?

Methodology

The methodology of this thesis is focused on the application of the SE processes through the use of LIs during the entire life span of an impact sled test project which includes the early planning phase from the point the Project Manager (PM) receives the project. The methodology of this thesis also focuses on how LIs can help improve portions of an impact sled test project. The first step is to determine what the top SE processes and LI trends are for the high speed test track environment and to chose a few LI trends on which to collect historical and current projects data. The second step is to determine the historical trend line for each of the chosen LI trends. The third step is to obtain trend lines for current projects for each of the chosen LI trends. The last step is to compare the historical trend lines to the current trends lines. By comparing the trend lines it can be determined if the current trend lines follow the historical trend lines and if LIs are a valuable resource for a high speed sled test project manager/engineer.

Assumptions/Limitations

An assumption for this thesis is the use of LI trends is still appropriate for short unique sled tests. The historical trend lines created in this thesis are for HHSTT impact tests. Other types of sled tests and other sled test facilities have different historical trends. Also, the PM will need to be very familiar with their test to determine if their project LI's should follow the historic trends.

Implications

If successful, the results of this thesis give an insight into the use of LI trends in a high speed sled test environment and show that they can be useful. A secondary result promotes the use of LI trends and SE processes in the test environment.

Preview

Chapter II presents the literature review, which includes research on SE in the testing community, the SE processes and LIs. Chapter III covers the methodology used to determine which SE processes the high speed sled test community currently emphasizes, values and uses; what LI trends are most relevant for use in a sled track environment and should be used; past historical data; and how the chosen historical LI trend lines compare to current LI trend lines. Chapter IV presents a summary of the findings. Chapter V concludes the thesis, provides discussion of the results and discusses future uses of LIs.

II. Literature Review

Chapter Overview

The purpose of this chapter is to address the resources used during the information gathering phase. This chapter will supply background on SE in the testing community, SE processes, and LI trends.

Systems Engineering (SE) in the Testing Community

Interest in applying SE to a test environment is present in the SE community as evidenced by a Systems Engineering and Test and Evaluation (T&E) conference held yearly where various SE and T&E organizations come together to discuss the use of SE during testing projects. (16,17) SE and the SE processes work best in the T&E community when a test is treated as a full program or project. Just like any other program, SE processes should be used throughout the testing process from inception through completion. (3,10)

System Engineering (SE) Processes

The *INCOSE Systems Engineering Handbook* (10) and the *Defense Acquisition Guidebook (DAG)* (3) both contain information and guidance on the SE processes and how to properly use them. The *DAG* is targeted toward the Department of Defense (DoD) and mainly used by military and DoD contractors. The *INCOSE Systems Engineering Handbook* is targeted to and used by the general public.

According to the *DAG* there are 16 key processes that should be used during a program's life cycle (Figure 3). They are split into two categories, technical management processes and technical processes. The technical management processes are used to manage the technical development of a system. These processes are normally conducted in increments. The technical processes are used to design the system. This also includes the systems and equipment that support the main system.

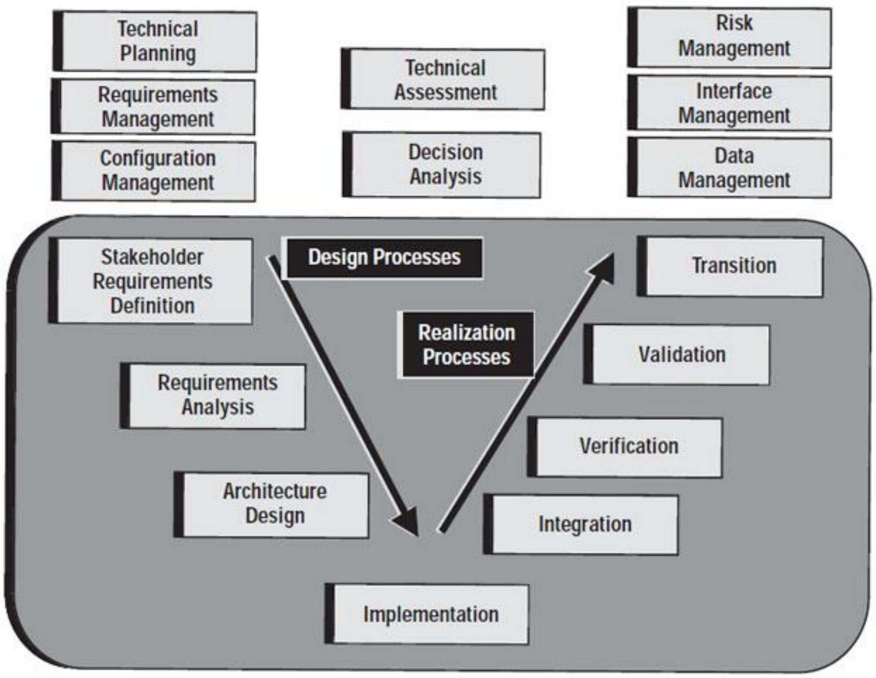


Figure 3: DAG Systems Engineering Processes (2)

According to the *INCOSE Systems Engineering Handbook* there are 18 different processes split into two different categories; project processes and technical processes (Figure 4). Project processes are similar to the *DAG* technical management processes. Both books have decision, planning, assessment, risk, and configuration processes. *Systems Engineering Handbook's* information management and measurement processes combined are very similar to *DAG's* technical data management and can achieve the same results. Technical processes for both books are also very similar. The *Systems*

Engineering Handbook has all of the *DAG* technical processes plus the addition of the operation, maintenance and disposal processes.

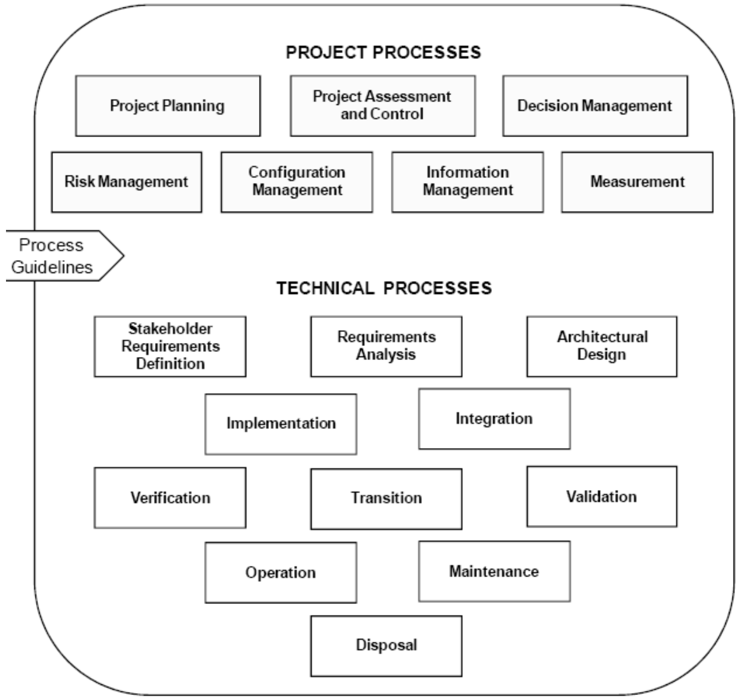


Figure 4: INCOSE Systems Engineering Processes (10)

Both the *DAG* and *Systems Engineering Handbook* offer insight into SE and the SE process. The decision on which book to use is dependent on the organization or person using the processes. The *DAG* is targeted towards military programs and is mainly used by Department of Defense (DoD) organizations and DoD contractors. The *Systems Engineering Handbook* is targeted towards and used more by the general SE population. Both books are extremely useful when conducting SE.

Leading Indicators (LI) Trends

According to the *Systems Engineering Leading Indicator Guide* “a leading indicator is a measure for evaluating the effectiveness of how a specific activity is applied on a project in a manner that provides information about impacts that are likely to affect the system performance objectives.” (12) An LI is a tool used to help predict the outcome of a project within a given confidence and time range which “provide[s] engineering leaders with the information they need to make informed decisions and, where necessary, take preventative or corrective action during the program in a proactive manner.” (13) In 2007, the first Systems Engineering Leading Indicator Guide (version 1.0) was issued with these 13 LI trends.

1. Requirements
2. System Definition Change Backlog
3. Interface
4. Requirements Validation
5. Requirements Verification
6. Work Product
7. Review Action Closure
8. Risk Exposure
9. Risk Handling
10. Technology Maturity
11. Technical Measurement
12. Systems Engineering Staffing & Skills
13. Process Compliance

According to version 2.0 of the *Systems Engineering Leading Indicator Guide* released in 2010 five additional LI trends were added.

14. Facility and Equipment Availability
15. Defect and Error
16. System Affordability
17. Architecture
18. Schedule and Cost Pressure

Traditional methods used to determine the trend of a program rely heavily on historical data and some current information. Although historical data is used, LIs rely heavily on the present and look to the future. "While leading indicators appear similar to existing measures and often use the same base information, the difference lies in how the information is gathered, evaluated, interpreted, and used to provide a forward looking perspective." (12) LIs are intended to be used on current and ongoing projects and use a graphical presentation to convey the information.

LIs consist of three parts: characteristics, conditions, and indications. The characteristics include needed information, leading insight, base measure specification, attributes, derived measures, and indicators (Appendix A). The base measures are used to determine the trend and are defined by a specific measurement method. The derived measures are formed by the base measures and describe one or more measures. (12) For example, one of the system definition change backlog base measures could be requests for change. An example of a derived measure linked to this base measure would be approval/closure rates which tracks the number of changes requested versus the number of change requests approved. The condition is the type of project or system that is being tracked. The outcome of combining the characteristics and a condition is an indication. The indication gives the organization a predicted behavior of the project for that specific trend. This information is normally presented graphically (Figure 5).

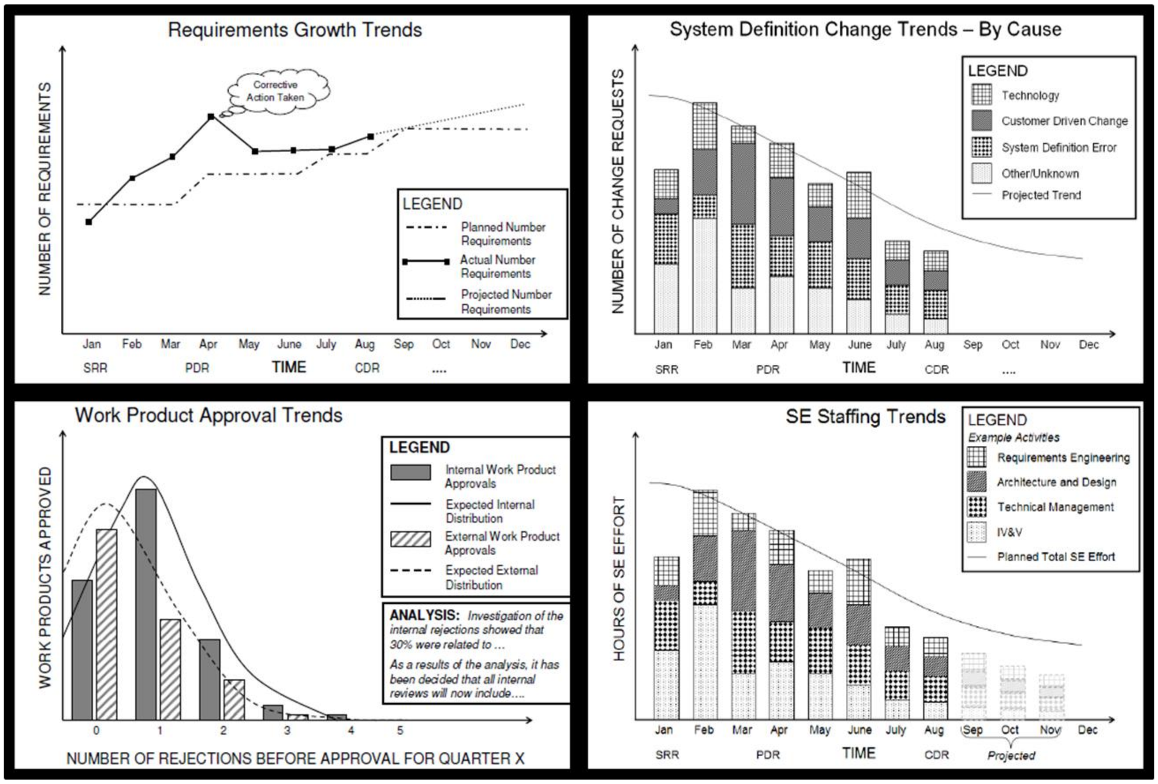


Figure 5: Sample LI Trend Graphs (11)

The time between collecting data for the chosen LIs will vary by the type of project, organization, and trend. PMs may want to collect data weekly, monthly, or quarterly. Data for the requirements trends LI might be collected every week while collecting data for the process compliance trends leading indicator might only be collected every month for the same project.

For a LI trend to be useful, the correct number and type of trends must be chosen. Choosing the wrong trend will give a false outcome. Choosing too many trends will take time away from the project and be too cumbersome to be useful. Choosing too few of the trends will not render sufficient information to make informed decisions. The number and type of LI trends to be used is dependent upon the size of the project, how much time the person or organization has to spend collecting and tracking the data and the type of project. The requirements, requirements validation, requirements verification and system definition change log trends are useful for projects that have a large number of requirements, a large number of last minute requirements or a large number of changes in the requirements. The interface trend is useful for projects that have a system with multiple parts or a system that will interface with multiple outside systems. The work product approval, review action closure, system engineering staffing and skill, and process compliance trends are all used to track different aspects within the organization throughout the progression of a project. Risk exposure and risk handling trends deal with program risk and are useful for programs with a large number of different risks or high risk items. Both technology maturity and technical measurement trends help projects that have a significant amount of and new technology associated with them. The facility and equipment availability trends are useful for organizations that use different facilities and types of equipment on multiple projects. The defect and error trend is useful with software development. The system affordability trends and schedule and cost pressure trends are useful for projects that are highly concerned with the budget and staying on schedule. The architecture trend is useful for large projects.

All of these LIs are useful and when used properly will help to make a program successful. However, not all LIs are useful for every project and choosing inappropriate LIs or the wrong number of LIs can be harmful to a project. Without insight into the project, LIs generate useless graphs that can give misleading information. However, if the Systems Engineer or PM chooses the right combination of LIs, then the use of LIs can be very successful.

Summary

The interest in using SE in testing environments has been presented. Both the *DAG* and *Systems Engineering Handbook* give beneficial insight into the SE processes and both are useful for projects in a testing environment. LI trends can also be used in a testing environment that appear to be similar to developmental projects – that is, the projects have requirements, develop modifications to existing components (test sleds and impact targets), plan to collect data, integrate non-developed items (customer provided test articles) and manage within cost and schedule.

III. Methodology

Chapter Overview

The purpose of this chapter is to illustrate the approach taken to determine which SE processes the high speed sled test community currently emphasizes, values and uses, and which LI trends are most relevant to a sled track environment. It will also illustrate the approach taken for data collection and compare the historical trend line to a current trend line for different LI trends.

Choosing System Engineering Processes

Determining which SE processes the high speed sled test community currently emphasizes, values and uses was completed using two different methods. The first method was to research SE processes that are currently and prominently being used. The second method was to determine what SE processes are thought to be useful to the high speed sled test community whether or not they are currently being utilized.

To obtain information on the current SE processes that are being prominently used in a high speed sled test environment, the HHSTT operations and procedures were reviewed. This review included project notes, squadron operational instructions (SOI) and meeting minutes. Personal experience conducting sled tests was also used to obtain this information.

To determine what SE processes are thought to be useful, an SE processes questionnaire was discussed with subject matter experts (SMEs) at the HHSTT (Appendix B). Data collection was received from ten members of the squadron including upper management, current and past PMs, data engineers and test engineers. The data set rated the importance of each process from 1 to 5, with 1 being most useful, to the projects conducted at the HHSTT. The second part of the data set ranked the 16 processes in usefulness to the HHSTT from 1 to 16, with 1 being the most useful.

Choosing Leading Indicator Trends

The information obtained from determining the SE processes the high speed sled test community currently emphasizes, values and uses, and a second questionnaire (Appendix C) were used to determine which LI trends are most relevant to the sled track environment.

The SE processes can be linked to different LI trends. The *Systems Engineering Leading Indicators Guide* links the LI trends to the INCOSE SE processes. For this thesis, data was collected from the HHSTT, a DoD organization. The SE guide most appropriate for the HHSTT is Chapter 4 of the *Defense Acquisition Guide (DAG)*. For this reason it is important to link the *DAG* SE processes to the different LI trends (Table 1). Using Table 1 the top LI trends can be determined from the top SE processes.

To obtain a complete picture of the most relevant LI trends, a second questionnaire was discussed with the same ten SMEs from the HHSTT squadron. Similarly to the previous data set, each LI trend was rated from 1 to 5 with 1 being most useful. The second part of the data set ranked the 18 trends in usefulness from 1 to 18 with 1 being the most useful. The top most useful LIs were determined by combining this survey with the SE processes data.

Table 1: SE Processes vs. LI Trends

		System Engineering Processes															
		Technical Planning	Requirements Management	Configuration Management	Technical Assessment	Decision Analysis	Risk Management	Interface Management	Data Management	Stakeholder Requirements Definition	Requirements Analysis	Architecture Design	Implementation	Integration	Verification	Validation	Transition
Leading Indicator Trends	Requirements		X							X	X						
	System Definition Change Backlog			X				X		X	X	X					
	Interface											X					
	Requirements Validation									X	X					X	
	Requirements Verification										X				X		
	Work Product Approval	X	X														
	Review Action Closure	X	X														
	Risk Exposure						X										
	Risk Treatment						X										
	Technology Maturity				X	X						X					X
	Technical Measurement					X				X	X	X	X	X			
	Systems Engineering Staffing & Skill	X	X														
	Process Compliance		X														
	Facility and Equipment Availability	X	X														
	Defect/Error	X	X														
	System Affordability					X				X	X	X					
	Architecture												X				
	Schedule and Cost Pressure	X	X														

Historical Trend Lines

LI trend lines from past impact tests needed to be collected. Two LI trends were selected for historical data collection. A historical trend line was created from different derived measures for each of the two chosen LI trends.

Four past impact tests from different customers were researched. Three separate PMs were associated with these four projects. These projects were selected because they were similar projects, considered to be typical impact tests for the HHSTT, yet included some dissimilar elements. All four tests were successful. Data was collected and recorded in weekly increments. For trend lines over time, the results were scaled to 40 weeks (about 10 months) and then an average was taken for each week. Historical bounds were used to determine a valid trend line range and used when comparing the current project trend lines to the historical trend lines. The historical bounds were found by determining the maximum and minimum values between each of the four historical projects at each data collection interval. This data was then compiled into line graphs.

Current Trend Lines

A Microsoft Excel™ LI tool (Appendix D) was created to collect and record the current trend lines for two of the top most useful LI trends. Users enter their current project start and end date and data collection rate. The tool then scales the historical trend line graphs to match the length of the current project. Users then enter their information at the intervals they have chosen. The end results are graphs with both historical and current trend lines along with the historical bounds. This tool was sent to two PMs at the HHSTT who each entered data from their current impact tests for a total of three tests. These projects were randomly chosen by the PMs.

Project A is 50 weeks long and the data was collected every two weeks up to week 30. The PM tracked only the high level requirements, a total of 11, for this project. Project B is 20 weeks long and the data was collected every two weeks up to week 12. The PM tracked the high and medium level requirements, a total of 26, for this project. The third project, Project C, is a short project of only 14 weeks and the data was collected every week up to week 11. The PM tracked high, medium and low level requirements for a total of 42. The graphs from the Microsoft Excel™ LI tool were used to compare the historical and current trend lines for these tests.

Summary

The top SE processes were determined using knowledge of the high speed test environment and a questionnaire. The top LI trends were determined by using the top SE processes and a second questionnaire. Historical data was collected from different HHSTT impact projects, scaled and graphed. Two HHSTT PMs contributed data for their current impact tests which was then graphically compared to the historical data. A total number of four past impact tests and three current impact tests were used to obtain the data.

IV. Analysis and Results

Chapter Overview

The purpose of this chapter is to show the data collected and results in determining which SE processes the high speed sled test community currently emphasizes, values and uses and which LI trends are most relevant to a sled track environment. Two LI trends were selected to analyze the historical and current trend. The results and comparison of these two LI trends are also reported in this chapter. All data collected was obtained from the HHSTT and squadron personnel.

Top System Engineering Processes

Researching the HHSTT project notes, SOIs and various project meeting minutes found the HHSTT is prominently using SE processes in their day-to-day conduct without focusing on SE or the SE processes. Out of the 16 *DAG* SE processes the HHSTT uses six on a regular basis (Table 2). These processes include requirements management, risk management, stakeholder requirements definition, validation, verification and interface management.

Table 2: SE Processes used at the HHSTT

~~Technical Planning~~
Requirements Management
~~Decision Analysis~~
~~Technical Assessment~~
Risk Management
~~Data Management~~
~~Requirements Analysis~~
Stakeholder Requirements Definition
Validation
Verification
~~Configuration Management~~
~~Integration~~
Interface Management
~~Architecture Design~~
~~Transition~~
~~Implementation~~

The first data collected from HHSTT squadron members was on SE processes to determine what processes are important to the HHSTT, even if they do not currently use the process. Because a process is not used does not mean the process should not be used. The first part of the questionnaire rated each of the processes from one to five. The second part of the questionnaire ranked all of the processes form one to 16. The results from the first portion of this questionnaire (Table 3) show the top two rate processes are technical planning and requirements management with averages of 1.20 and 1.40, respectively. Tied for third with an average of 1.60 are decision analysis, technical assessment and risk management processes. The results from the second portion of this questionnaire (Table 4) show the technical planning and requirements management processes are tied for the top ranked processes with an average of 3.40. Risk management and data management are tied for third with an average of 3.70.

Table 3: SE Processes Survey Individually Rated

SE Processes	Average	S Deviation
Technical Planning	1.20	0.63
Requirements Management	1.40	0.70
Decision Analysis	1.60	0.70
Technical Assessment	1.60	0.70
Risk Management	1.60	0.84
Data Management	1.90	1.10
Requirements Analysis	2.00	0.82
Stakeholder Requirements Definition	2.50	0.53
Validation	2.80	1.69
Verification	3.10	1.52
Configuration Management	3.30	1.06
Integration	3.60	1.17
Interface Management	3.70	1.06
Architecture Design	3.90	0.88
Transition	4.10	1.10
Implementation	4.50	0.53

Table 4: SE Processes Survey Group Ranked

SE Processes	Average	S Deviation
Technical Planning	3.40	1.17
Requirements Management	3.40	2.12
Risk Management	3.70	3.02
Data Management	3.70	3.30
Stakeholder Requirements Definition	6.00	3.37
Technical Assessment	6.40	2.67
Requirements Analysis	6.60	2.07
Decision Analysis	7.70	3.97
Configuration Management	9.60	2.17
Validation	9.70	4.14
Interface Management	10.00	2.21
Verification	11.90	3.67
Architecture Design	12.00	1.83
Integration	12.00	2.00
Implementation	14.60	1.07
Transition	15.30	0.95

By combining all the data from the two questionnaires and SE processes the HHSTT currently utilizes, the top three SE processes the high speed sled test community currently emphasizes, values and uses were determined. These processes are the requirements management, risk management and technical planning processes (Table 5). Even though technical planning is not prominently used currently at the HHSTT, it was chosen as one of the top two because in both sections of the questionnaire it was rated and ranked as number one.

Table 5: Top SE Processes

SE Processes	Currently Used	Questionnaire Part 1 Top 3	Questionnaire Part 2 Top 3
Requirements Management	X	2	1
Risk Management	X	3	3
Technical Planning		1	1
Interface Management	X		
Stakeholder Requirements Definition	X		
Verification	X		
Validation	X		
Decision Analysis		3	
Technical Assessment		3	
Data Management			3
Configuration Management			
Requirements Analysis			
Architecture Design			
Implementation			
Integration			
Transition			

Top Leading Indicators Trends

Finding the top three most relevant trends consists of looking at the top SE processes and the top rated and ranked LI trends. Linking the SE processes to LI trends results in multiple possibilities for the top two trends. Fifteen possible LI trends can be linked to the six prominently used SE processes (Table 6). These trends include requirements, system definition change backlog, requirements validation, requirements verification, work product approval, review action closure, risk exposure, risk treatment, technical measurement, SE staffing and skill, process compliance, facility and equipment availability, defect/error, system affordability, and schedule and cost pressure. Any of these fifteen trends may be useful. More information is needed to narrow the selection down to the top three most relevant LI trends.

Taking into account the top three SE processes found in the above section, requirements management, risk management and technical planning processes, the number of LI trends decreases to ten (Table 7). These trends include requirements, work product approval, review action closure, risk exposure, risk treatment, SE staffing and skill, process compliance, facility and equipment availability, defect/error, and schedule and cost pressure. Again, any of these ten LI trends could be relevant. To determine which of these ten LI trends are the top trends or if any of these are the top trends, the second questionnaire was needed.

Table 6: Prominently Used SE Processes vs. LI Trends

		System Engineering Processes															
		Technical Planning	Requirements Management	Configuration Management	Technical Assessment	Decision Analysis	Risk Management	Interface Management	Data Management	Stakeholder Requirements Definition	Requirements Analysis	Architecture Design	Implementation	Integration	Verification	Validation	Transition
Leading Indicator Trends	Requirements		X							X	X						
	System Definition Change Backlog			X				X		X	X	X					
	Interface											X					
	Requirements Validation									X	X					X	
	Requirements Verification										X				X		
	Work Product Approval	X	X														
	Review Action Closure	X	X														
	Risk Exposure						X										
	Risk Treatment						X										
	Technology Maturity				X	X						X					X
	Technical Measurement					X				X	X	X	X	X			
	Systems Engineering Staffing & Skill	X	X														
	Process Compliance		X														
	Facility and Equipment Availability	X	X														
	Defect/Error	X	X														
	System Affordability					X				X	X	X					
	Architecture												X				
	Schedule and Cost Pressure	X	X														

Table 7: Top SE Processes vs. LI Trends

Leading Indicator Trends	Technical Planning	Requirements Management	Configuration Management	Technical Assessment	Decision Analysis	Risk Management	Interface Management	Data Management	Stakeholder Requirements Definition	Requirements Analysis	Architecture Design	Implementation	Integration	Verification	Validation	Transition
Requirements		X							X	X						
System Definition Change Backlog			X				X		X	X	X					
Interface											X					
Requirements Validation									X	X					X	
Requirements Verification										X				X		
Work Product Approval	X	X														
Review Action Closure	X	X														
Risk Exposure						X										
Risk Treatment						X										
Technology Maturity				X	X						X					X
Technical Measurement					X				X	X	X	X	X			
Systems Engineering Staffing & Skill	X	X														
Process Compliance		X														
Facility and Equipment Availability	X	X														
Defect/Error	X	X														
System Affordability					X				X	X	X					
Architecture												X				
Schedule and Cost Pressure	X	X														

(Column group heading: System Engineering Processes)

Data collected from HHSTT squadron members for the second questionnaire composed of LI trends to determine what trends are important to the HHSTT. The first part of the questionnaire rated each of the LI trends from one to five while the second part ranked all of the trends from one to 18. The findings from the first part of the questionnaire (Table 8) show the most relevant LI trend is the requirements trend with an average of 1.30. Tied for second, with an average of 1.50, are the requirements validation trend and the facility and equipment availability trend. The results from the second part of the questionnaire (Table 9) show the two most relevant trends with an average 2.40 are the requirements and requirements validation trends. The results from both portions of the questionnaire are consistent with each other showing the same top three LI trends.

Combining both the LI trends questionnaire and the results from the SE processes, the number of relevant LI trends drops to two, requirements and facility and equipment availability trends (Table 10). In order to determine the top three relevant LI trends, a third trend was selected from the LI questionnaire results by its' ranking and rating. This makes the top three LI trends the requirements, facility and equipment availability, and requirements validation trends. Two of these trends are linked to an SE process that is currently prominently being used in the high speed testing community. The requirement validation trend is a trend that the high speed sled track testing community believes would be relevant tying second in rating and first in ranking.

Table 8: LI Trend Questionnaire Individually Ranked

LI Trends	Average	S Deviation
Requirements	1.30	0.48
Requirements Validation	1.50	0.53
Facility and Equipment Availability	1.50	0.53
Requirements Verification	1.80	0.92
Schedule and Cost Pressure	1.90	0.99
System Affordability	2.40	1.26
Technical Measurement	2.50	1.51
Risk Exposure	2.60	0.97
Work Product Approval	2.80	0.79
Risk Handling	2.80	0.79
Review Action Closure	3.00	1.15
Process Compliance	3.00	1.15
Defect and Errors	3.30	1.34
System Engineering Staffing & Skill	3.40	1.07
System Definition Change Log	3.60	0.70
Interface	3.80	0.92
Technology Maturity	4.00	1.15
Architecture	4.50	0.85

Table 9: LI Trend Questionnaire Group Ranked

LI Trends	Average	S Deviation
Requirements	2.40	3.10
Requirements Validation	2.40	1.84
Facility and Equipment Availability	3.40	1.17
Requirements Verification	5.30	3.50
System Affordability	7.20	2.66
Schedule and Cost Pressure	7.30	2.83
Review Action Closure	8.10	4.28
Defect and Errors	8.90	3.90
Risk Exposure	9.10	1.85
Risk Handling	10.30	2.06
System Engineering Staffing & Skill	10.40	4.72
Work Product Approval	10.90	2.85
Process Compliance	12.00	3.56
Technical Measurement	12.30	4.19
Technology Maturity	14.00	3.40
Interface	14.60	4.70
System Definition Change Log	15.40	3.06
Architecture	16.40	1.78

Trend Lines

The requirements and requirements validation trends were chosen to create historical trend lines. The *Systems Engineering Leading Indicator Handbook* gives nine suggested derived measures for the requirements trend. These measures include percent requirements approved, percent requirements growth, percent to-be-determined (TBD)/to-be-reviewed (TBR) closure variance per plan, percent requirements modified, estimated impact of requirements change, requirement defect profile, requirement defect density, requirement defect leakage and cycle time for requirement changes. The first five of the nine suggested derived measures are relevant to the HHSTT and are a good fit. The HHSTT does not actively track defects making the sixth, seventh, and eighth derived measures not very useful. The ninth derived measure was not chosen because the HHSTT does not precisely record overtime hours and the PMs do not have the means at their disposal to determine the start and stop time of overtime hours, only the total amount of overtime used each week. The *Systems Engineering Leading Indicator Handbook* suggests two derived measures for the requirements validations trend: requirements validation rate and percent requirements validated. Both of these suggested derived measures are relevant to the HHSTT. The first five derived measures from the requirements trend and both of the derived measures from the requirements validation trends will be used. When collecting data, the type of requirements were divided into customer requirements and squadron derived requirements to gain greater insight into the projects, as suggested by the *Systems Engineering Leading Indicator Handbook*. The next sections describe the seven LI measures used.

Table 10: Top SE Processes vs. Top LI Trends

	System Engineering Processes															
Leading Indicator Trends	Technical Planning	Requirements Management	Configuration Management	Technical Assessment	Decision Analysis	Risk Management	Interface Management	Data Management	Stakeholder Requirements Definition	Requirements Analysis	Architecture Design	Implementation	Integration	Verification	Validation	Transition
Requirements		X							X	X						
System Definition Change Backlog			X				X		X	X	X					
Interface											X					
Requirements Validation									X	X					X	
Requirements Verification										X				X		
Work Product Approval	X	X														
Review Action Closure	X	X														
Risk Exposure						X										
Risk Treatment						X										
Technology Maturity				X	X						X					X
Technical Measurement					X				X	X	X	X	X			
Systems Engineering Staffing & Skill	X	X														
Process Compliance		X														
Facility and Equipment Availability	X	X														
Defect/Error	X	X														
System Affordability					X				X	X	X					
Architecture												X				
Schedule and Cost Pressure	X	X														

Percent Requirements Approved Derived Measure

The trend lines for the percent requirements approved derived measure are percentages graphed over time. This derived measure takes into account the number of approved requirements versus the number of identified requirements and uses the equation:

$$\left(\frac{requirements\ approved}{requirements\ identified}\right) \times 100$$

The historical trend lines suggest that during the first week of the project between 50 and 60 percent of the customer requirements and between 30 and 40 percent of the derived requirements should be approved (Figures 6 & 7). By the time the project is 50 percent complete the trend lines suggest the majority of both customer and derived requirements should be approved. By the time the project is 75 percent complete all the requirements should be approved. At no point do any of the historical bounds differ from the trend line more than 32 percent for the customer requirements and 31 percent for the derived requirements. Having the project trend lines above the historical trend lines is a positive result and indicates a stable project. Having the project trend lines below the historical trend lines is a negative result. If the project trend line is significantly below the historical trend line, the PM should investigate why requirements are not being approved and determine if actions need to be taken to ensure the requirements are being approved in a timely manner.

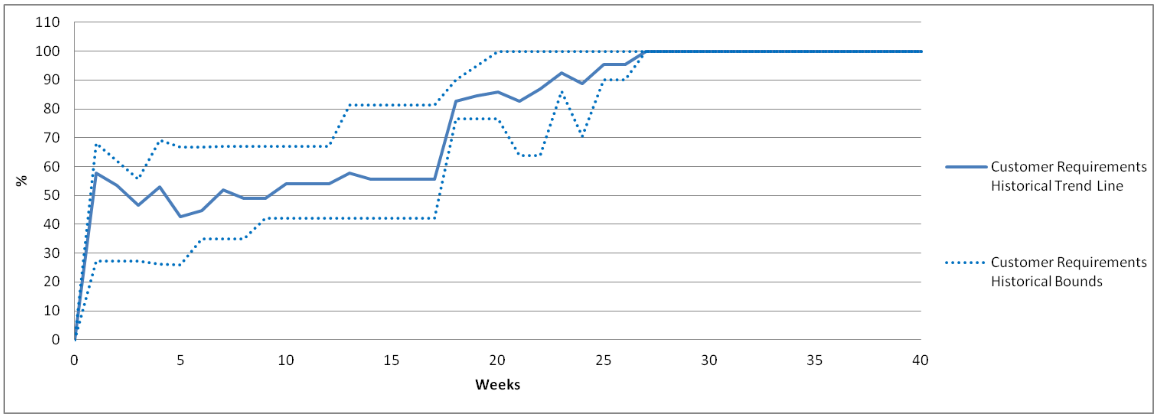


Figure 6: Percent of Customer Requirements Approved Historical Trend Lines

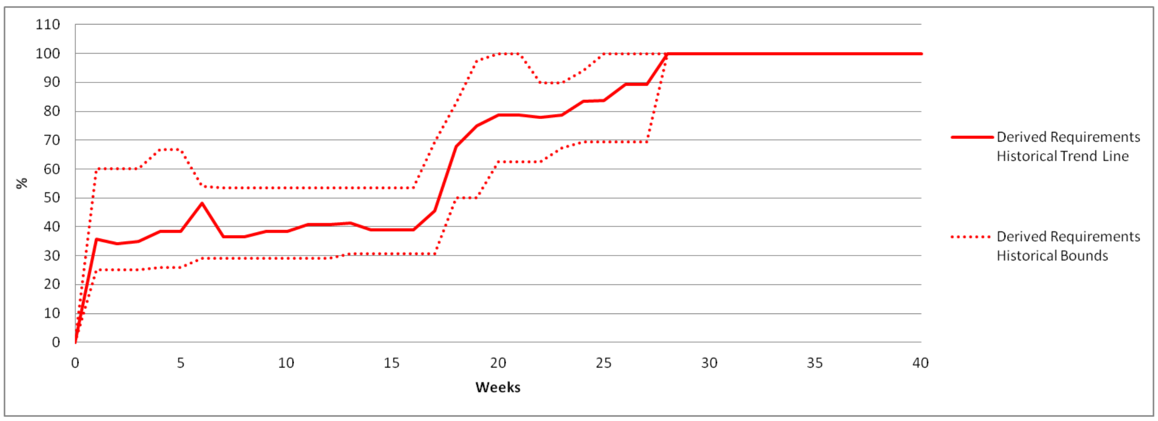


Figure 7: Percent of Derived Requirements Approved Historical Trend Lines

Combining the project trend lines with the historical trend lines gives insight into where the project is heading and if there need to be any corrections made. Project A's customer requirements trend line falls within the historical bounds 50 percent of the time while the derived requirements trend lines falls within the bounds 57 percent of the time (Figures 8 & 9). The trend lines suggest the customer requirements have all been approved and are well ahead of the curve. At no point during the project does the customer requirements trend line fall below the lower historical bound, and by week nine, the trend line shoots well above the upper bound. In this case not following the historical trend line is a positive result because the number of requirements approved is ahead of historical norms. The project derived requirements trend line shows that the rate at which requirements are being approved is slower than the customer requirements, even though the trend line is within the historical bounds by 7 percent more than the customer requirements trend line.

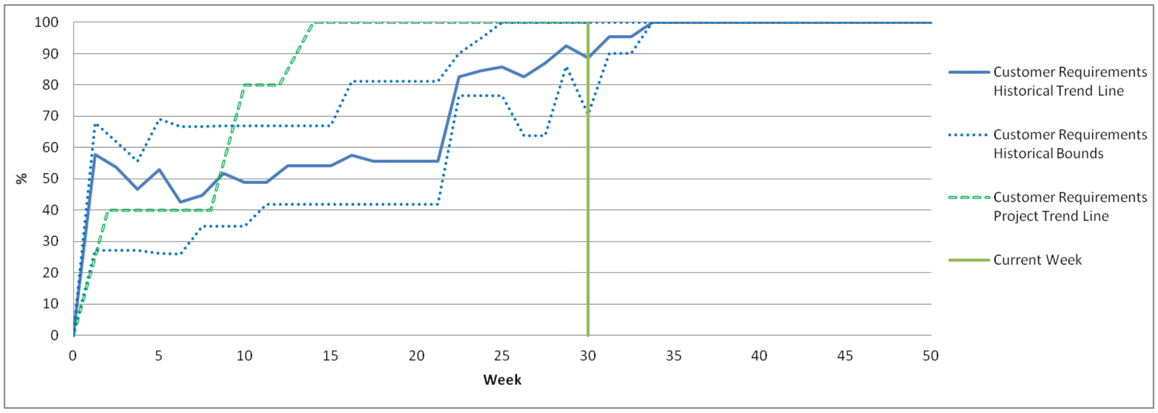


Figure 8: Project A Percent of Customer Requirements Approved Trend Lines

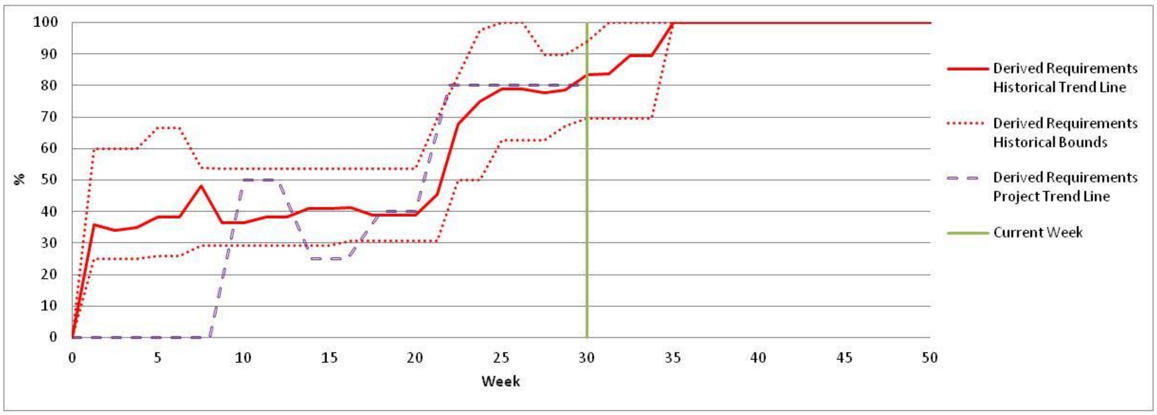


Figure 9: Project A Percent of Derived Requirements Approved Trend Lines

Project B's trend lines follow the historical trend lines more closely and fall within the historical bounds for the customer requirements and derived requirements 67 percent and 50 percent of the time, respectively (Figures 10 & 11). The project's customer requirements trend line follows the historical trend line closely until about week eight when the historical trend starts to increase, leaving the project trend line behind. This should raise a red flag for PM and should be investigated due to the fact that the project trend line does not only fall below, with a maximum difference of 17 percent, the historical trend line, but it also falls below the historical bound line. By week 12, the customer project trend line still has not caught up to the historical trend line and barely skims the historical bound line by one percent. This leads to the conclusion that there might be a problem. If not handled soon, the schedule might slip or the cost might increase. For the majority of the project, the derived requirements project trend line is above or very close to the historical line and never falls below the historical bound line. This should not be a concern for the PM.

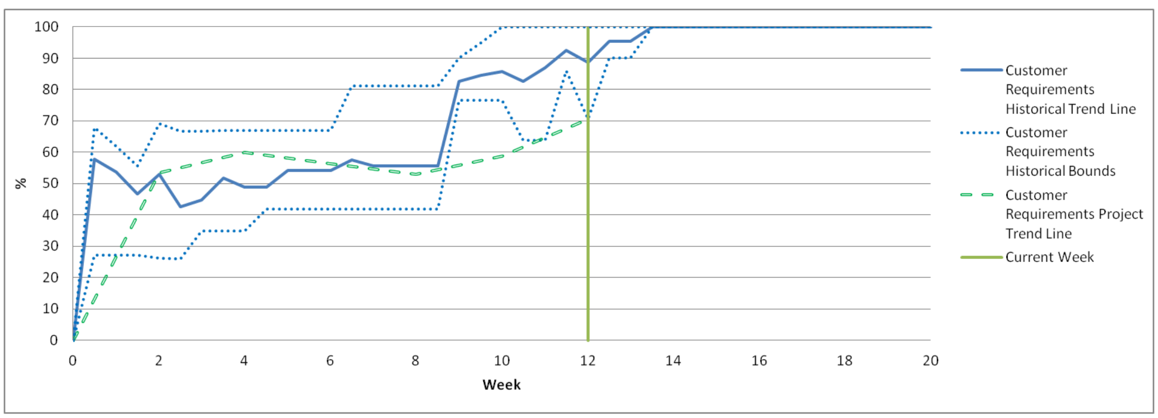


Figure 10: Project B Percent of Customer Requirements Approved Trend Lines

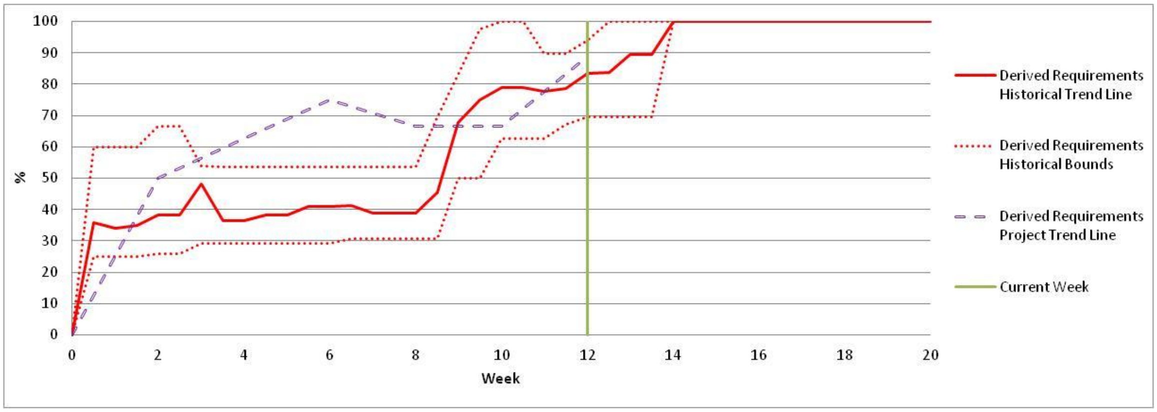


Figure 11: Project B Percent of Derived Requirements Approved Trend Lines

Project C's trend lines are very different from the historical trend lines and generally do not fall within the historic bounds with only 45 percent of the customer requirements trend line and 0 percent of the derived requirements trend line within the bounds (Figures 12 & 13). According to the historical trend lines all requirements should be approved by week 10. The project trend lines show that about 80 percent of the customer requirements and 55 percent of the derived requirements have been approved. Without the historical trend lines, the PM may view these results as normal because for most projects it may take a few weeks for the requirements to be approved. However, with the historical trend lines scaled to 14 weeks, there is clear proof that the PM should be concerned and actions should be taken quickly before the project schedule slips and costs increase.

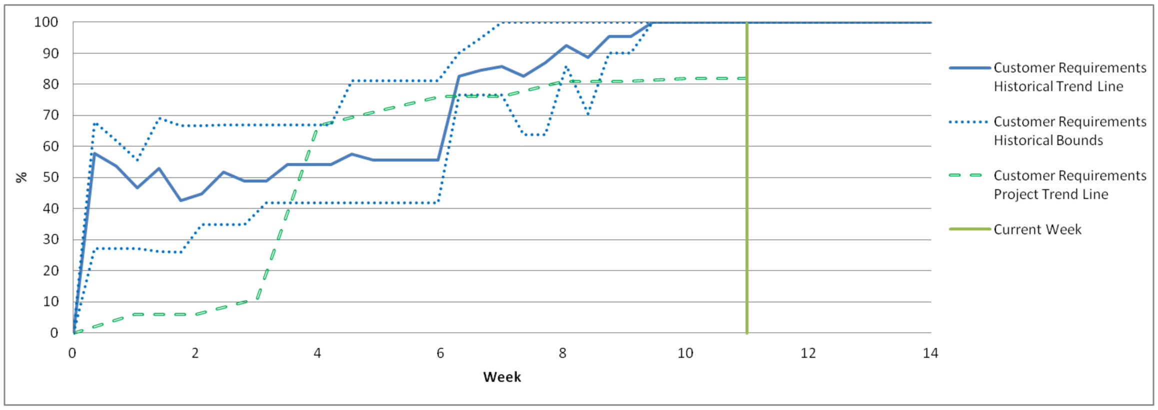


Figure 12: Project C Percent of Customer Requirements Approved Trend Lines

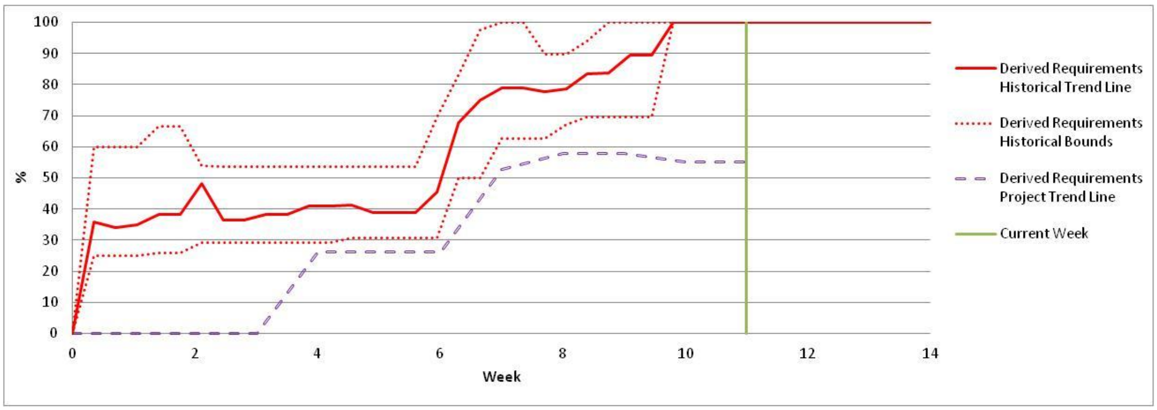


Figure 13: Project C Percent of Derived Requirements Approved Trend Lines

Out of the six project trend lines, four of them fell within the historical bounds at least 50 percent of the time, and one did not fall within the bounds at any time during the project. For Project A's customer requirements trend line, having the trend line fall outside of the bounds should not be considered negatively. This simply means the project did not follow the historical data but rather was ahead of the historical trend.

Percent Requirements Growth Derived Measures

The trend lines for percent requirements growth derived measure are percentages graphed over time. This derived measure takes into account the number of new requirements versus the number of old requirements and uses the equation:

$$\left(\frac{number\ of\ new\ requirements}{number\ of\ old\ requirements}\right) \times 100$$

By applying this derived measures' equation to the historical and project data, a graph with multiple spikes is created (Figure 14). This graph is very hard for the PMs to interpolate. To help improve the way the information is displayed, the percentage determined at each collection interval was added to the previous interval using the equation:

$$\sum_{i=1}^{current\ week} \left\{\left[\left(\frac{number\ of\ new\ requirements}{number\ of\ old\ requirements}\right) \times 100\right]_i\right\}$$

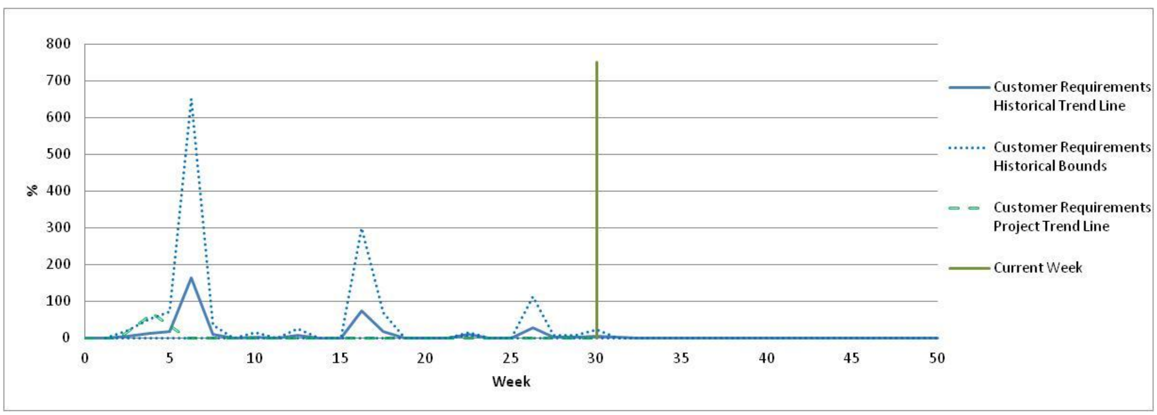


Figure 14: Sample Percent of Growth Derived Measures

By applying the second equation to the historical information, more insight is gathered for this derived measure. The customer requirements historical bound lines are overly wide for this derived measure (Figure 15). After week five the upper bound is never less than 374 percent away from the historical trend line with a maximum difference of 457 percent. The lower bound is closer with a minimum difference of 192 percent and a maximum difference of 290 percent. The derived requirements historical bound lines fall closer to the historical trend line but are still very wide (Figure 16). After week five the upper bound has a difference between 76 and 151 percent, and the lower bound has a difference between 88 and 144 percent. Having such wide historical bounds show that the historical projects do not match each other when it comes to requirements growth. This also implies that this data is not reliable.

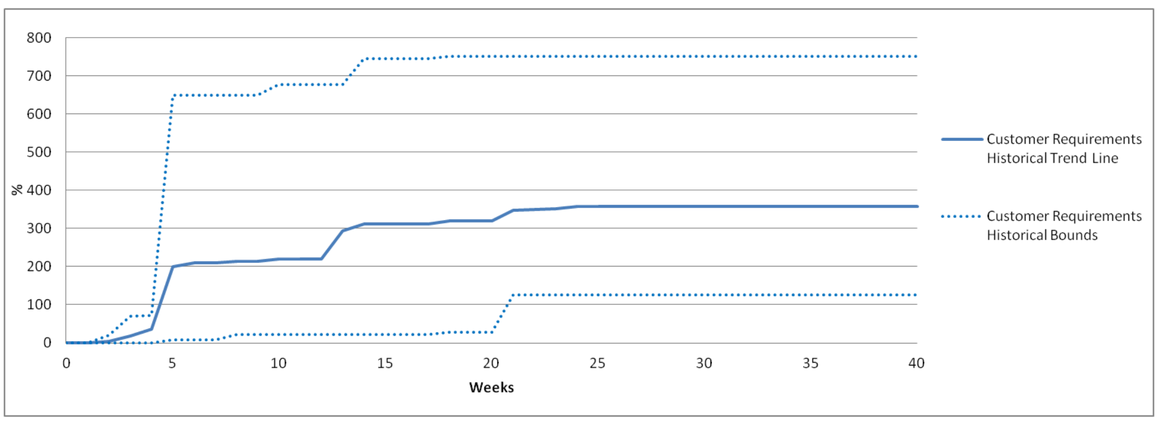


Figure 15: Percent of Customer Requirements Growth Historical Trend Line

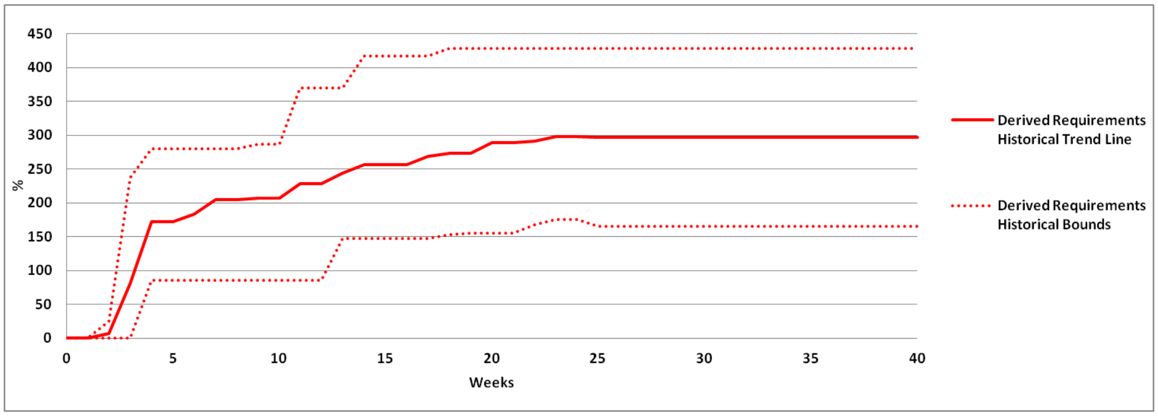


Figure 16: Percent of Derived Requirements Growth Historical Trend Line

The project trend lines for Project A do not match with the historical trend lines and the derived requirements never fall within the historical bounds (Figures 17 & 18). The customer requirements trend line does fall within the historical bounds for 83 percent of the project but is still over 100 percent away from the historical trend line for the majority of the project. The project trend line shows that the majority of the customer equipments were received within the first five weeks of the project and the derived requirements were received around week 14. One reason these lines do not match may be the lack of requirements recorded for the project. The project looked at high level requirements only while the historical data included all levels of requirements. Another reason for the discrepancy between the project and historical lines is the unreliability of the historical information for this derived measure.

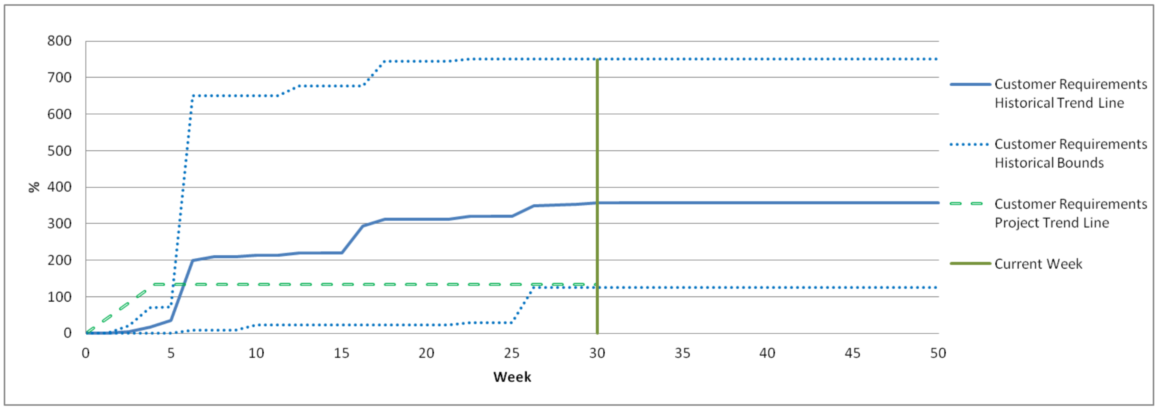


Figure 17: Project A Percent of Customer Requirements Growth Trend Lines

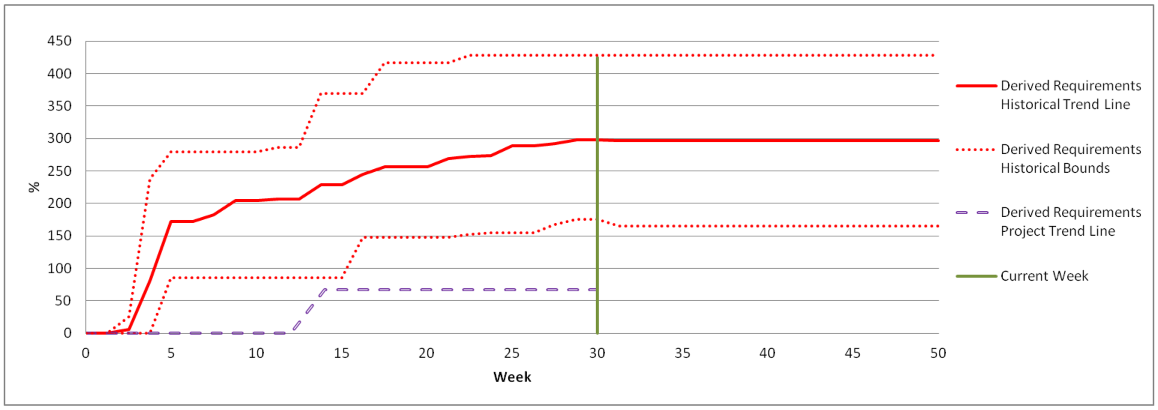


Figure 18: Project A Percent of Derived Requirements Growth Trend Lines

Project B trend lines also do not follow the historical trend lines and neither of the trend lines rise above the low historical bound (Figures 19 & 20). The customer requirements trend line and the lower historical bound line have a maximum difference of 118 percent while the derived requirements trend line has a maximum difference of 98 percent from the historical trend line. The customer requirements trend line only increases by seven percent which leads to the conclusion that either there is the lack of requirements and more are expected in the future or the majority of the requirements were received the first day of the project. Like Project A, a reason for the trend lines not matching could be a result of the lack of requirements recorded for the project and the unreliability of the historical information for this derived measure. Project B recorded more requirements than Project A but still not as many as the historical projects recorded.

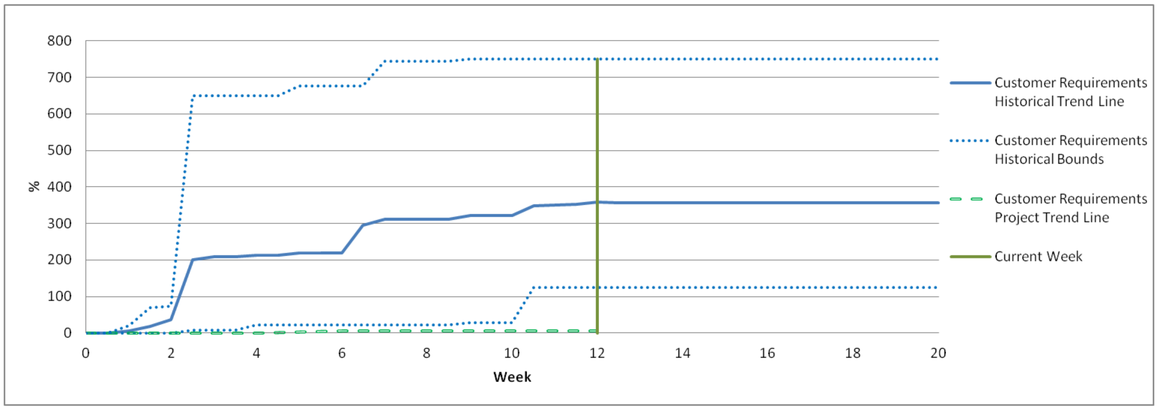


Figure 19: Project B Percent of Customer Requirements Growth Trend Lines

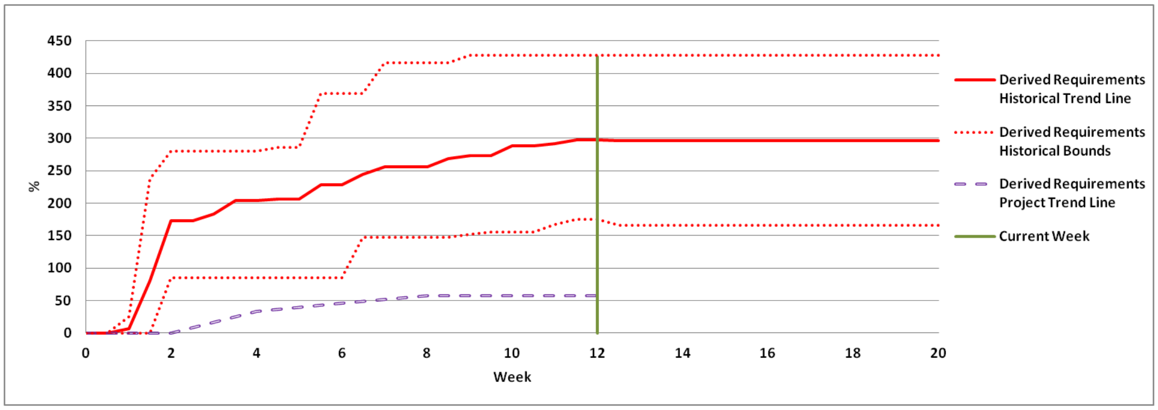


Figure 20: Project B Percent of Derived Requirements Growth Trend Lines

As in the previous two projects, Project C trend lines do not match the historical trend lines (Figures 21 & 22). Also, neither type of requirement falls within the historical bounds. The customer requirements trend line stays well below the historical bounds, never increasing more than 27 percent. The derived requirements trend line spikes to 1800 percent at week four never getting closer than 1372 percent to the upper bound line.

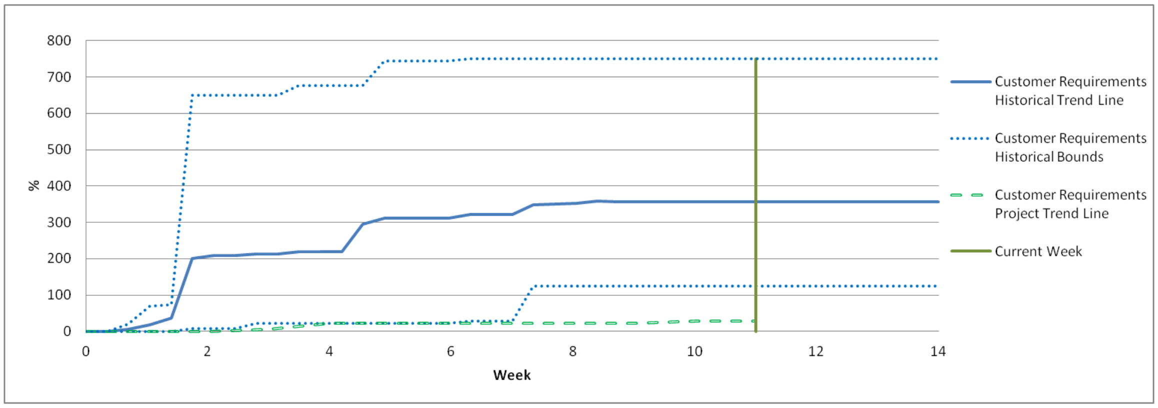


Figure 21: Project C Percent of Customer Requirements Growth Trend Lines

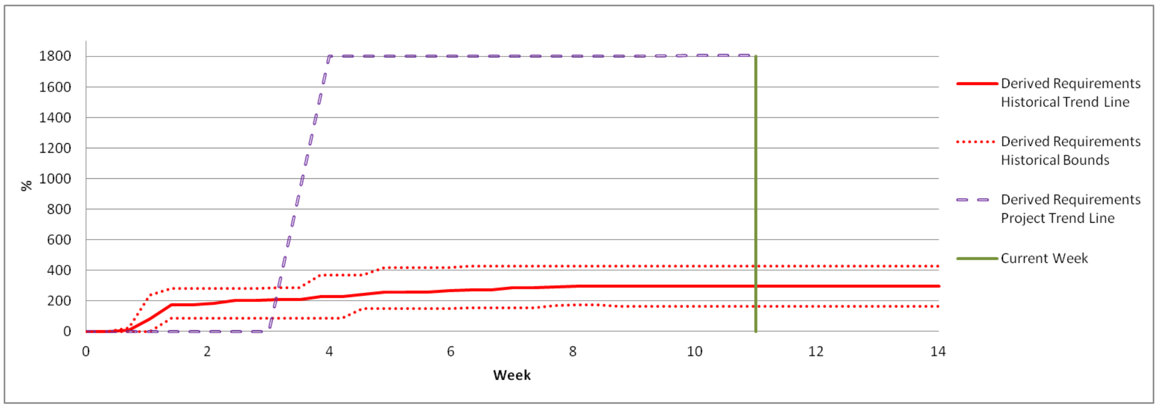


Figure 22: Project C Percent of Derived Requirements Growth Trend Lines

None of the projects trend lines follow the historical trend lines or fall within the requirements historical bounds, with the exception of Project A's customer requirements, for the percent requirements growth derived measure. The wide historical bounds also make this derived measure very unreliable.

Percent To-Be-Determined/To-Be-Reviewed Closure Variance Derived Measures

The trend lines for percent TBD/TBR closure variance derived measure are percentages graphed over time. This derived measure takes into account the number of requirements TBD/TBR versus the number of TBD/TBR requirements that have been closed. The derived measure uses the equation:

$$\left(\frac{(TBD/TBR\ planned\ for\ closure) - (TBD/TBR\ closed)}{TBD/TBR\ planned\ for\ closure}\right) \times 100$$

The historical trend line suggests that at no point during the project should the percent of TBD/TBR customer requirements be over 87 percent and derived requirements be over 75 percent (Figures 23 & 24). It also suggests that halfway through the project the amount of TBD/TBR requirements should be no more than 40 percent open, and by the time the project is three-fourths complete there should be no open TBD/TBR requirements. The customer requirements historical bound is slightly wider than the derived requirements historical bound with a minimum difference of seven percent and a maximum difference of 36 percent versus a minimum difference of seven percent and maximum difference of 29 percent. For this derived measure, having the project trend lines below the historical trend lines is a positive result. If the project trend lines are above the historical trend lines, the PM should look into why TBD/TBR requirements are not being closed and if any actions need to be taken to ensure requirements are being closed in an acceptable time frame.

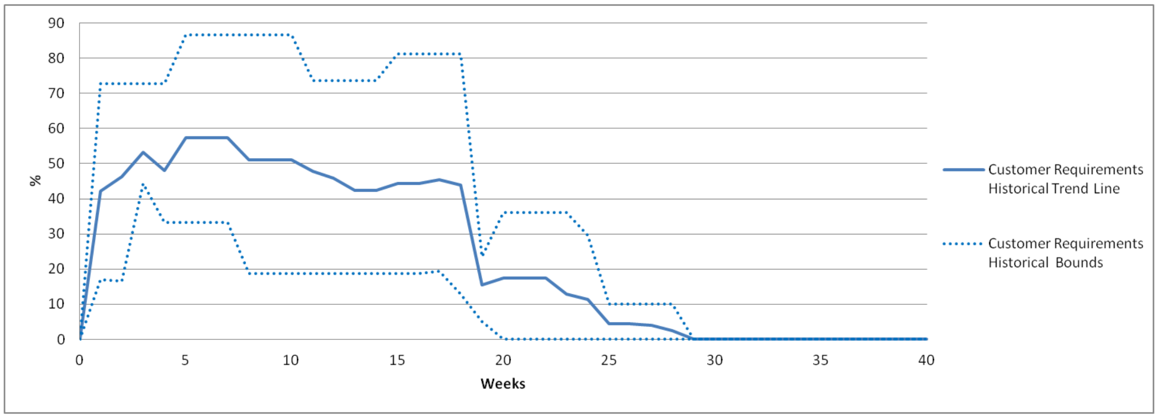


Figure 23: Percent of Customer Requirements TBD/TBR Closure Variance Historical Trend Line

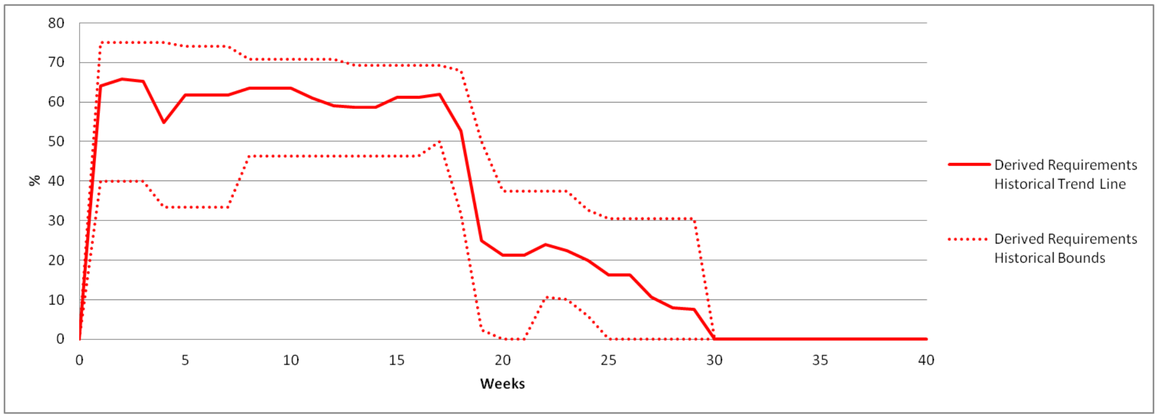


Figure 24: Percent of Derived Requirements TBD/TBR Closure Variance Historical Trend Line

Project A's trend lines do not match the historical trend lines and rarely stay within the historical bounds (Figures 25 & 26). The customer requirements trend line falls within the bounds only 17 percent of the time while the derived requirements trend line falls within the bounds 7 percent of the time. Even though the customer requirements project trend line does not follow the historical information, there is nothing wrong with the number of customer requirements the project has TBD/TBR. Having no requirements TBD/TBR is rare but a very good thing. In contrast, the derived requirements project trend line starts well above the historical upper bound with a difference of 25 percent. The PM should be concerned that none of the derived requirements have been approved. However, around week 13 this concern should be lessened, and by week 16 there should be no major concern about the number of unapproved derived requirements.

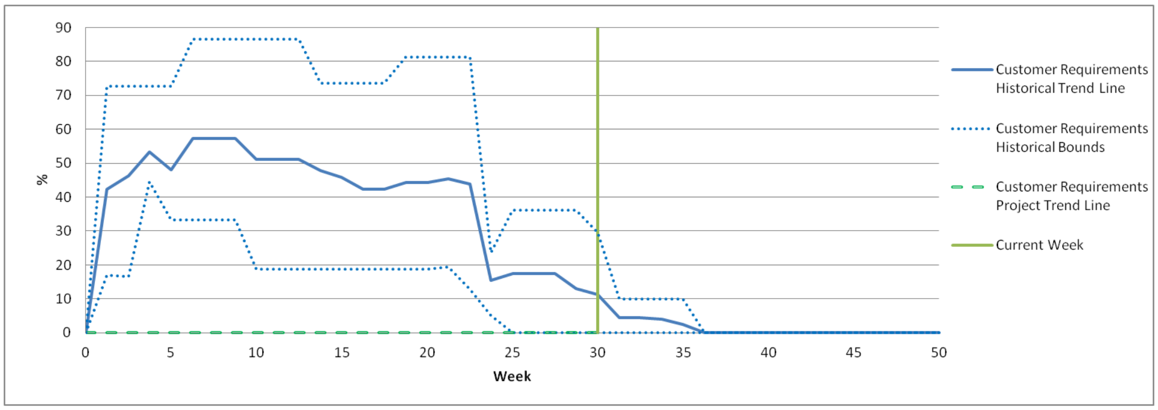


Figure 25: Project A Percent of Customer Requirements TBD/TBR Closure Variance Trend Lines

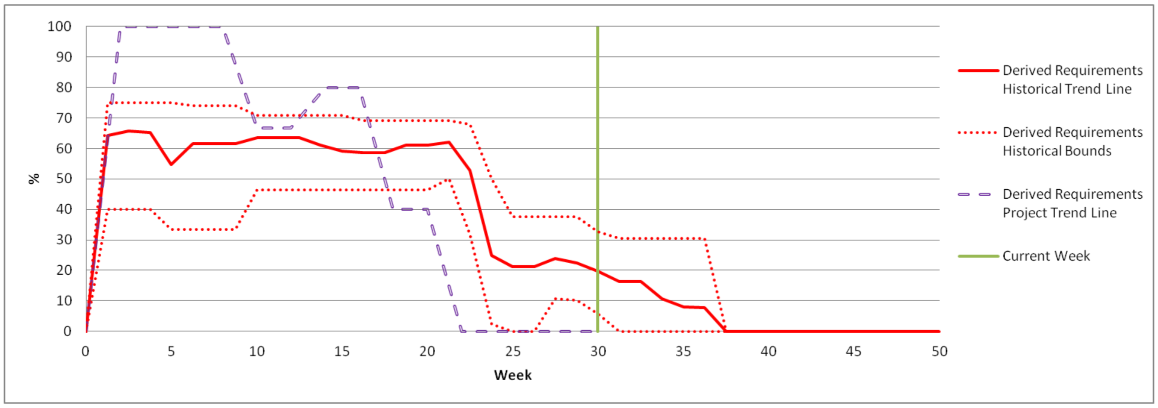


Figure 26: Project A Percent of Derived Requirements TBD/TBR Closure Variance Trend Lines

Project B's trend lines closely matches the historical trend lines and stays within or below the requirements historical bounds (Figures 27 & 28). The customer requirements trend line stays within the historical bounds 83 percent of the time. The derived requirements trend line stays within the historical bounds only 32 percent of the time, but this should not a negatively viewed thing. Having fewer TBD/TBR requirements is a positive outcome. The PM should not be overly concerned with this aspect of the project and can concentrate more of his time on other aspects of the project. However, if the project's derived requirements trend line continues on its current path by week 15, the PM should be concerned and investigate why the derived requirements have not been determined.

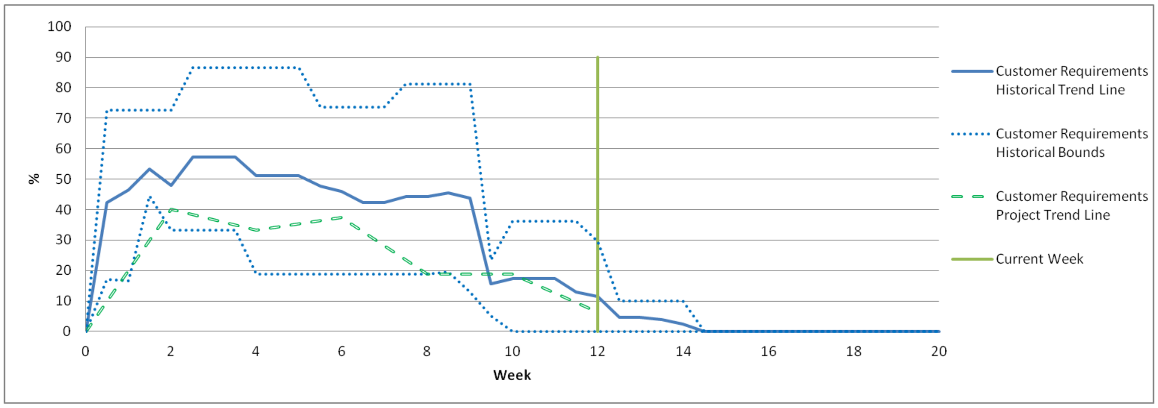


Figure 27: Project B Percent of Customer Requirements TBD/TBR Closure Variance Trend Lines

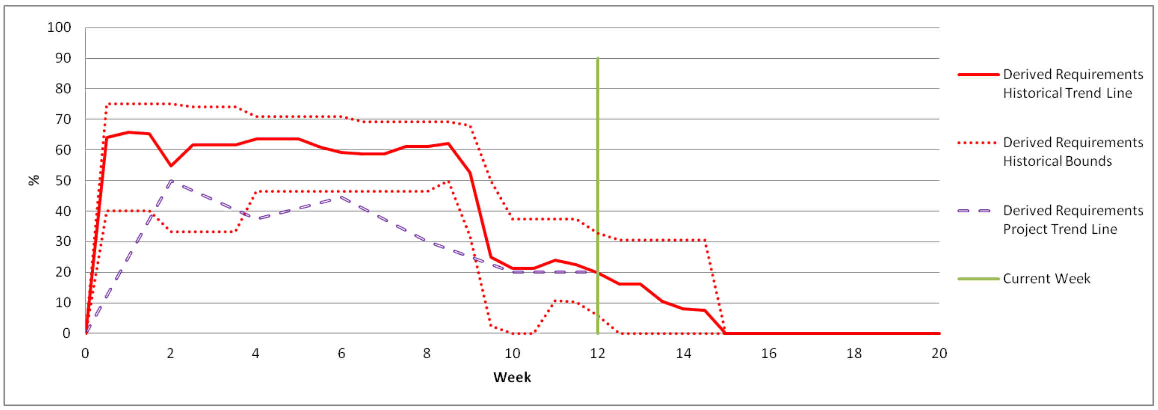


Figure 28: Project B Percent of Derived Requirements TBD/TBR Closure Variance Trend Lines

Project C's trend lines are close to the historical trend lines for a portion of the project, but also exceed the upper historical bound (Figures 29 & 30). The project requirements trend line stays within the bounds for 73 percent of the project and the derived requirements trend line for 36 percent of the project. Early into the project the percentage of the project's customer requirements that need TBD are well above the historical trend line but still stays within the historical bound. The PM should not be overly concerned with this portion of the project until around week nine when the project trend line exceeds the historical bound by 13 percent. On the other hand, the PM should be concerned with the derived requirements from the start of the project with the trend line exceeding the historical bound by 25 percent. After week six the project line falls below the upper historical bound; however, at week ten the project trend line starts to exceed the upper bound by 30 percent.

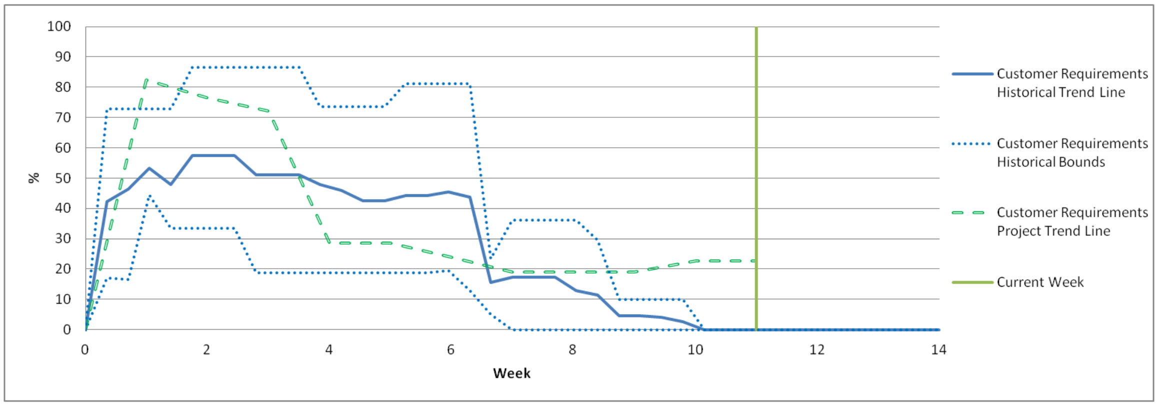


Figure 29: Project C Percent of Customer Requirements TBD/TBR Closure Variance Trend Lines

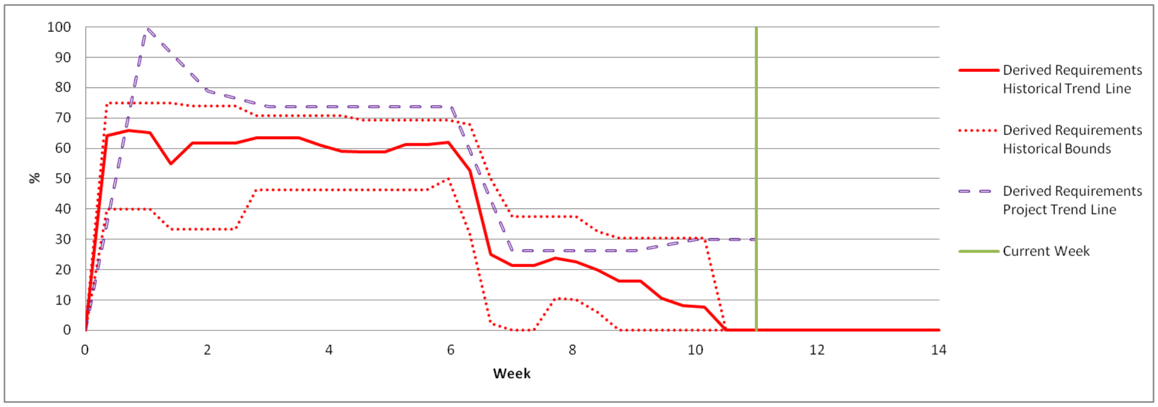


Figure 30: Project C Percent of Derived Requirements TBD/TBR Closure Variance Trend Lines

Of the three projects, Project B follows the historical trend lines the closest and stays within the historical bounds most often. However, Project A's customer requirements trend line had the best outcome with no TBD/TBR requirements during the project even though the trend line did not always fall within the historical bounds. Project A illustrates that not following the historical trend line does not have to be a negative outcome; it simply indicates that the project is not typical and does not follows the historical information.

Percent Requirements Modified Derived Measures

The trend lines for percent requirements modified derived measure are percentages graphed over time. This derived measure takes into account the number of requirements modified versus the number of total requirements and uses the equation:

$$\left(\frac{total\ number\ of\ requirements\ modified}{total\ number\ of\ requirements}\right) \times 100$$

The historical trend suggests that a significant number of requirements are modified within the first part of the project and gradually increases until the end (Figures 31 & 32). From the trend data, at no point should the number of modified requirements be greater than 35 percent. Other than between weeks ten and 12, the customer requirements historical bound stays within 16 percent of the customer requirements historical trend line. During weeks ten and 12, the upper historical bound increases to a difference of 22 percent. This jump between weeks ten and 12 is due to a historical out layer. The derived requirements historical bound is more jagged, but always stays within 19 percent of the historical trend line. For this derived measure, having the project trend lines below the historical trend lines is a positive outcome. However, the PM should be aware that a significant number of modified requirements could occur later into the project. Having the project trend lines above the historical trend lines is a negative outcome. This suggests that the project is unstable and that the PM needs to keep a close watch on the requirements.

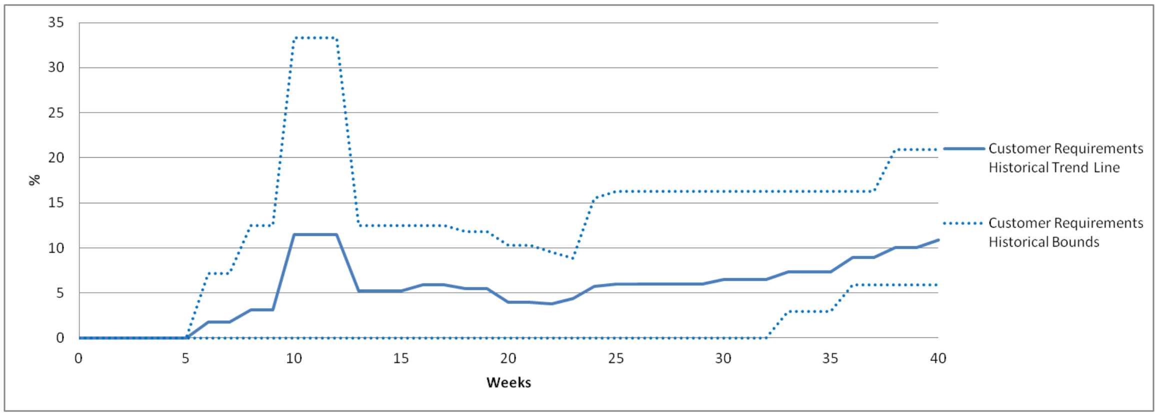


Figure 31: Percent Customer Requirements Modified Historical Trend Line

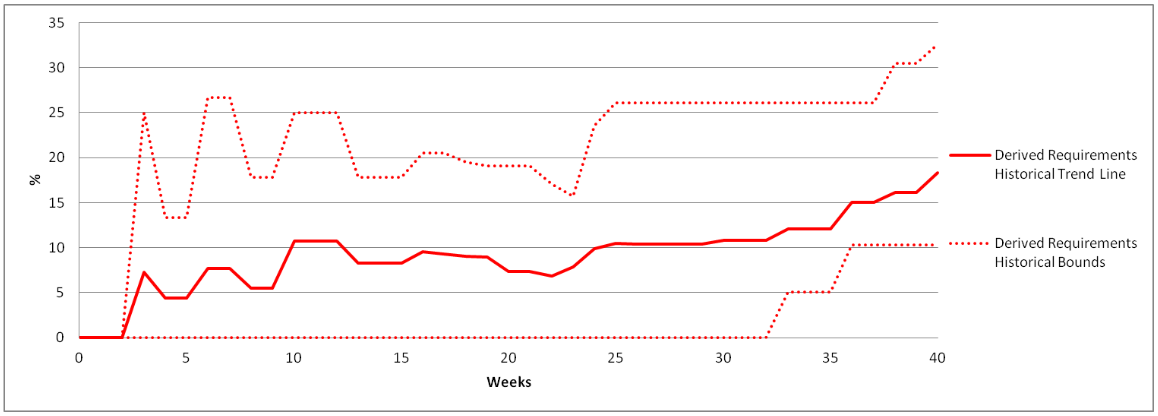


Figure 32: Percent Derived Requirements Modified Historical Trend Line

The percentage of modified requirements for Project A is highly unusual, and therefore the project trend lines do not match the historical trend lines (Figures 33 & 34). It is uncommon to have so many of the requirements modified during any part of a project. From the beginning of the project, the percent of requirements that were modified jumped well above the historical percentage and continued to climb. By week 30 the customer requirements trend line is 164 percent above the customer requirements historical upper bound line, and the derived requirements trend line is 429 percent above the derived requirements historical upper bound line. The given data suggests this is an extremely unstable project and the PM should be highly concerned.

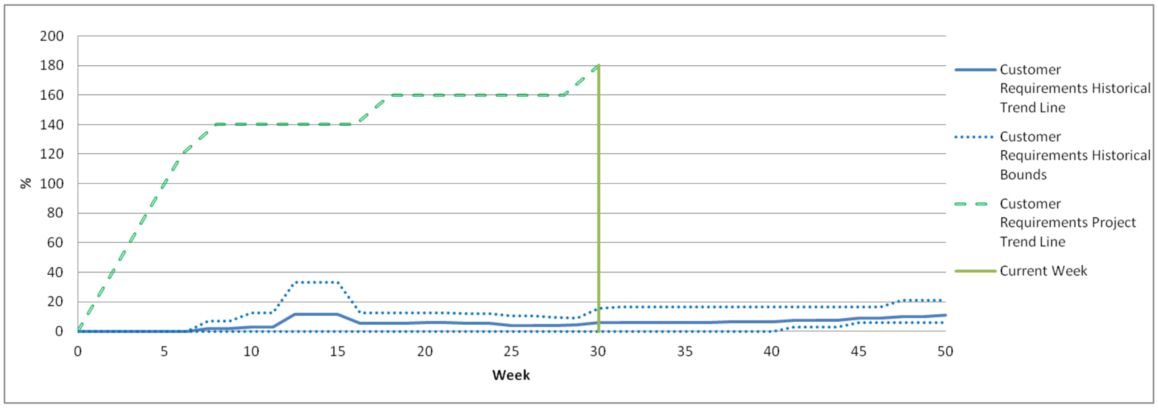


Figure 33: Project A Percent Customer Requirements Modified Trend Lines

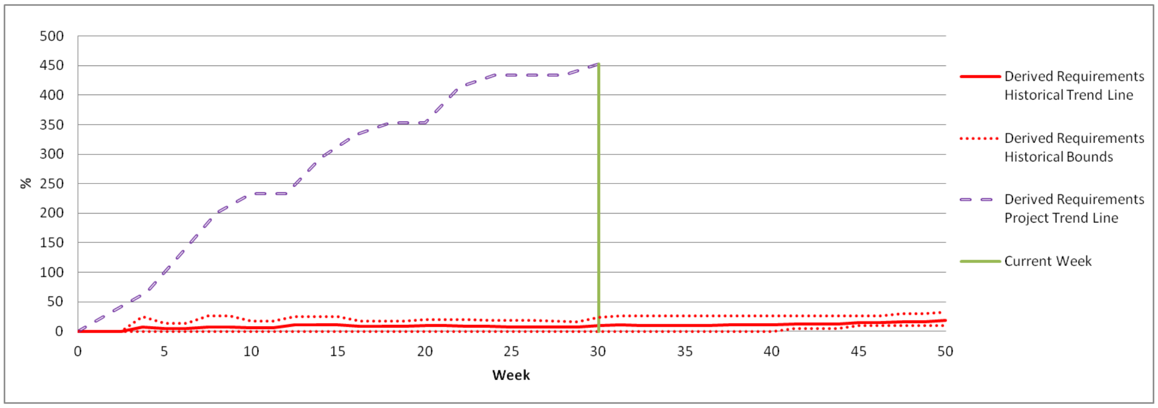


Figure 34: Project A Percent Derived Requirements Modified Trend Lines

Project B's project trend lines also do not match the historical trend lines, but is well within the requirements historical bounds for 100 percent of the project (Figures 35

& 36). The PM of this project should not be concerned about the number of requirements that have been modified. The first half of the project was very stable and had no modified requirements. During week 12, requirements started to be modified and exceeded the historical percentages but stayed within the requirements historical bounds.

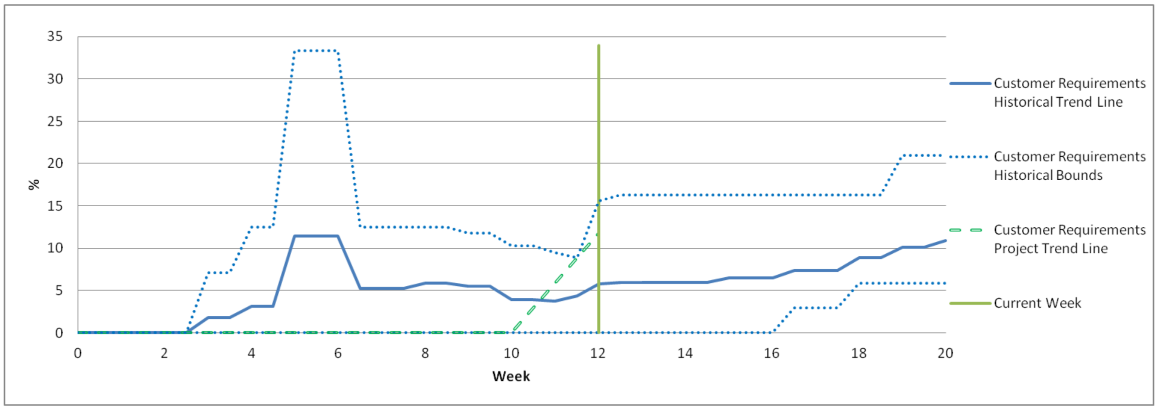


Figure 35: Project B Percent Customer Requirements Modified Trend Lines

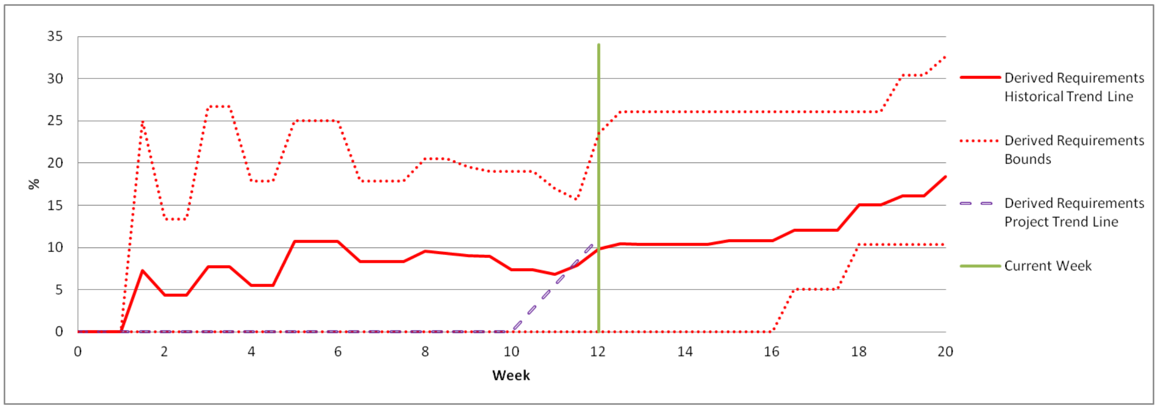


Figure 36: Project B Percent Derived Requirements Modified Trend Lines

Project C is similar to Project B where no requirements are modified until late into the project, and both trend lines stay within the historical bounds for 100 percent of the project (Figures 37 & 38). This project does not receive any modified customer requirements until the project is over 70 percent complete, and there currently are no modified derived requirements. This is a very stable project. The information gives the PM insight into what the general trend of a project could be and increases the expectations that more requirements might be modified before the end of the project.

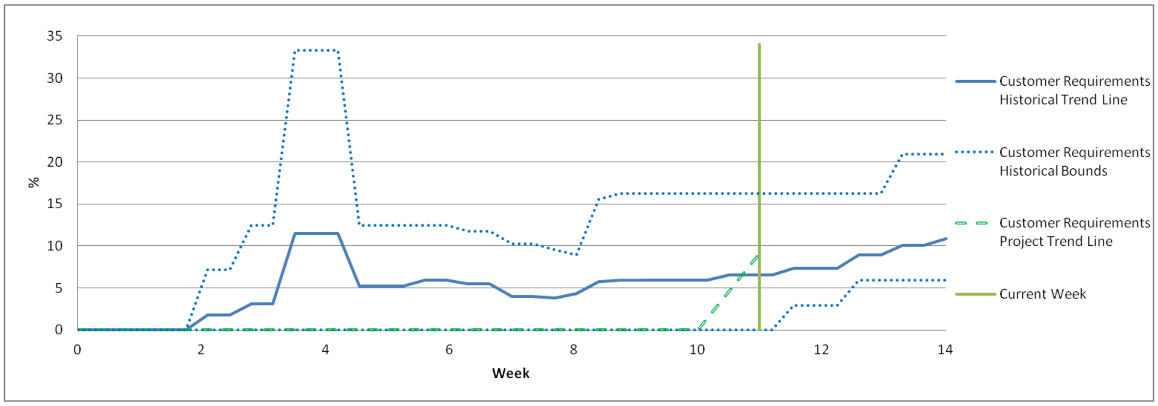


Figure 37: Project C Percent Customer Requirements Modified Trend Lines

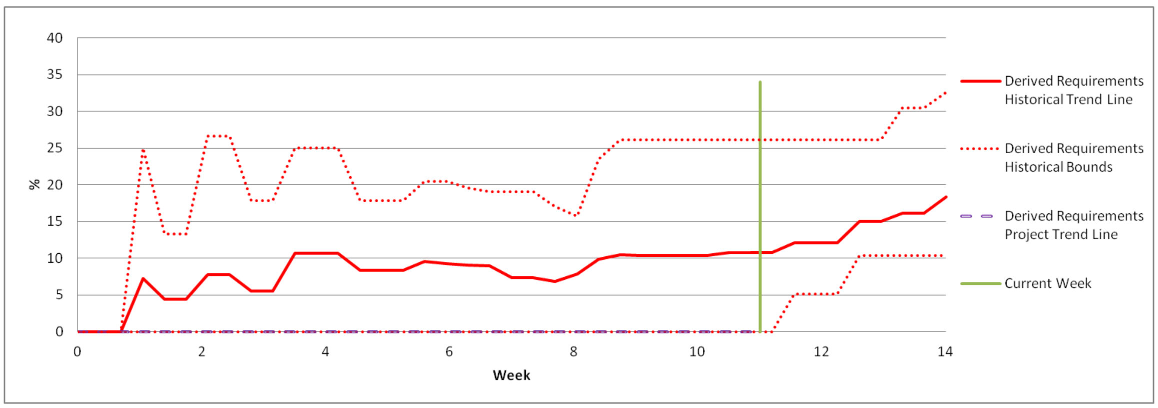


Figure 38: Project C Percent Derived Requirements Modified Trend Lines

Both Project B and C stayed within the requirements historical bounds and did not receive any modified requirements until late into their projects. Project A was not close to the requirements historical bounds due to the rarity of how many modified requirements were involved.

Estimated Impact of Requirements Change Derived Measures

The trend lines for the estimated impact of requirements change derived measure are summations over time. This derived measure takes into account the number of overtime hours worked during the entire project. The type of requirements for this derived measure was not split into customer and project requirements due to the type of information to which the PMs had access. The PMs only have easy access to the amount of overtime worked for their project each week. They do not have easy access as to which requirement caused the overtime. Obtaining this information would take more time than they have available. Overtime hours have multiple causes and are not limited to requirements change. This derived measure should be combined with other derived measures, such as the percent of modified requirements derived measure, for the data to be valid.

The historical trend suggests that the majority of overtime is worked toward the end of a project and spikes significantly during the last few weeks (Figure 39). The historical bounds range between six and 18 hours above the historical trend line and between two and 14 hours below. A large number of overtime hours occurring at the beginning of a project is not common and needs to be investigated by the PM.

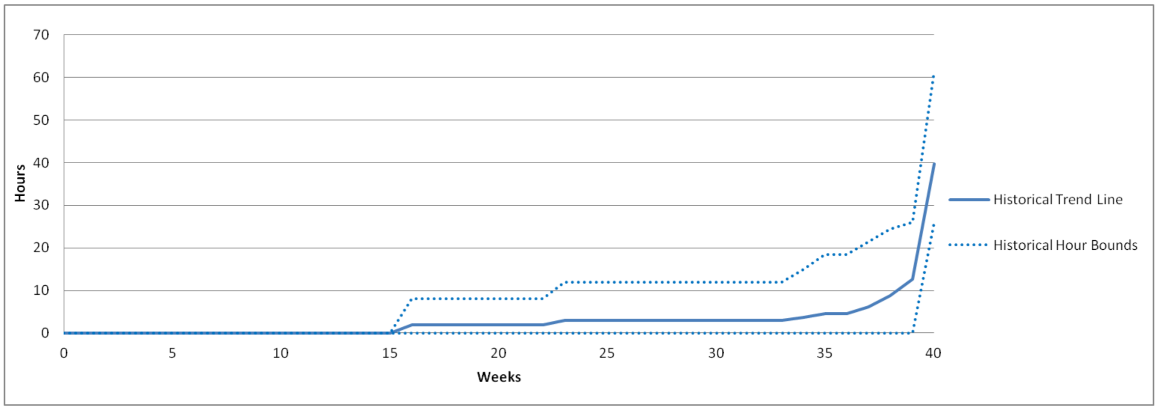


Figure 39: Estimated Impact of Requirements Change Historical Trend Line

The amount of overtime used for Project A starts off high and increases as the project progresses (Figure 40). This links directly back to the number of modified requirements recorded with the previous derived measure, percent requirements modified. By week 30, the number of hours worked on Project A exceeds the historical bounds by 242 hours. The PM should be very concerned about the amount of overtime being used and should take corrective actions if possible along with notifying the customer that there will most likely be a cost overrun and/or a project schedule extension. The derived measure shows that this much overtime is not normal and that the amount of overtime is likely to continue to increase during the remainder of the project.

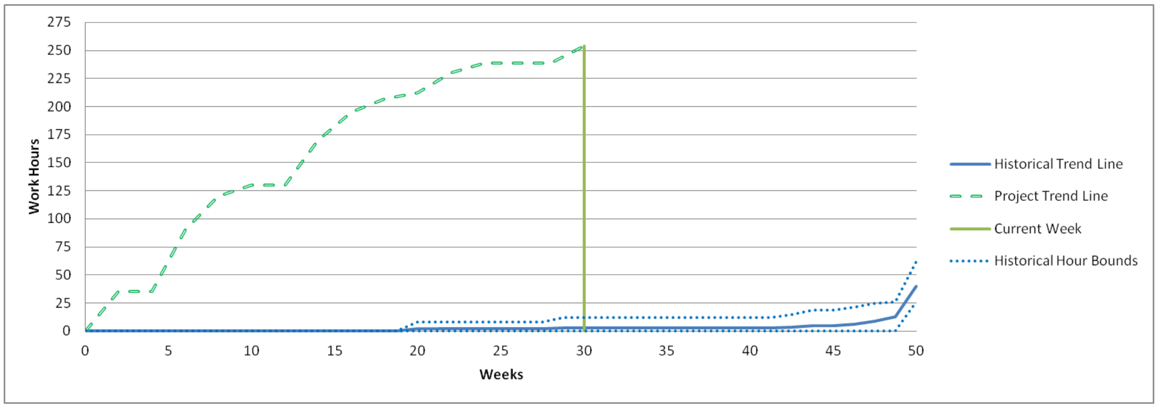


Figure 40: Project A Estimated Impact Requirements Change Trend Lines

The project trend line for Project B is close to the historical trend line and stays within historical hour bounds for the entire project (Figure 41). The project did not require overtime hours until week 12, which is consistent with the point at which the requirements started to be modified. Although the amount of overtime for the project at week 12 is more than double the amount of the historical data, the PM should not be overly concerned because it is still within the historical bounds. However, the PM should keep an eye on the amount of overtime accumulated and expect to incur additional overtime towards the end of the project.

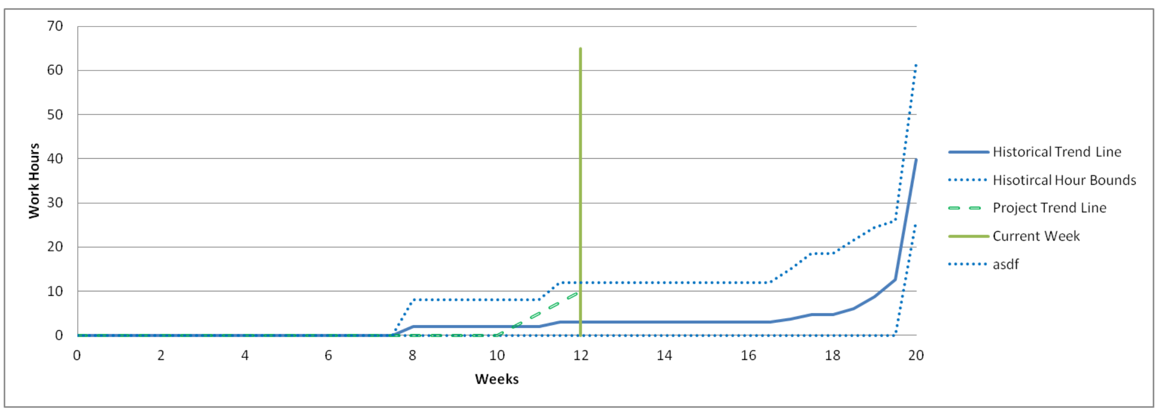


Figure 41: Project B Estimated Impact Requirements Change Trend Lines

Project C did not incur any overtime; therefore, its project trend line does not follow the historical trend line but stays within the historical bounds (Figure 42). The derived measure informs the PM that there is a high probability that overtime will be used before the end of the project and that the PM should expect the majority of the overtime to occur after the 12th week.

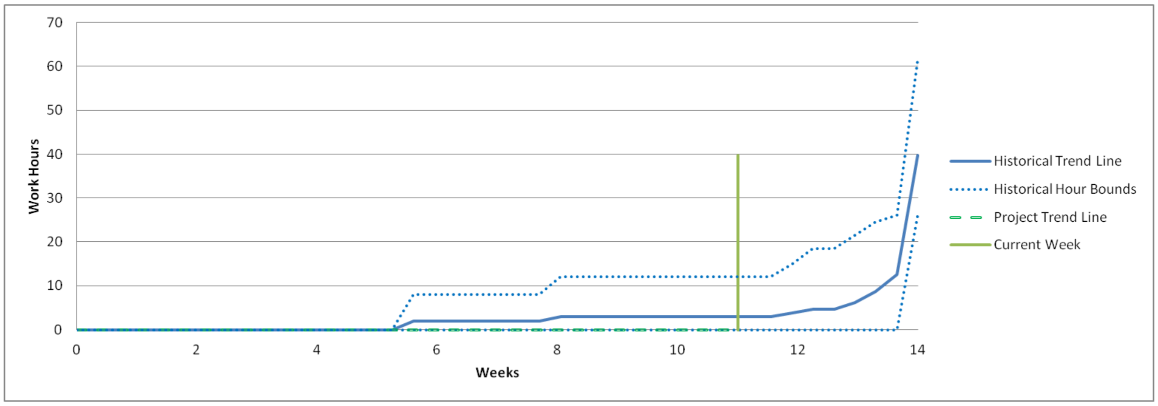


Figure 42: Project C Estimated Impact Requirements Change Trend Lines

For the information provided in this derived measure to be valid, it must be combined with other derived measures. This is due to the fact that overtime is the result of multiple factors and is not limited to requirements change. For these three projects, the derived measure links back to the percent requirements modified derive measure. As requirements are modified, the PM should expect some amount of overtime to be used. Except for Project A, the project trend lines fell within the historical hour bounds for 100 percent of the project and the projects results were favorable. This derived measure gives valuable insight at the beginning of the project to budget for extra overtime in case it is needed.

Requirement Validation Rate Derived Measure

The trend lines for the requirement validation rate derived measure takes into account the length of the time it takes for a requirement to be validated in terms of weeks. For example, the amount of requirements that were validated within one week of receiving the requirement was calculated. This derived measure is determined by using the equation:

$$\frac{(date\ requirement\ added) - (date\ requirement\ validated)}{7\ days}$$

Utilizing the equation above, the result depends heavily on the amount of requirements recorded in the historical and current projects (Figure 43). The amount of requirements varies greatly between the different projects making it hard to compare the different trend lines. The graphs for this derived measure also only contain information for requirements that have already been validated. As more requirements are validated, the entire shape of the graph may change. To make it easier to compare the different trends lines the percent of requirements validated over a period of time was calculated. For example, the percent of requirements that were validated within one week of receiving the requirement was calculated. The new equation is:

$$\sum_{i=1}\left[\left(\frac{\left(\frac{(data\ requirements\ added) - (date\ requirement\ validated)}{7\ days}\right) \leq i}{total\ number\ of\ requirements}\right) \times 100\right]$$

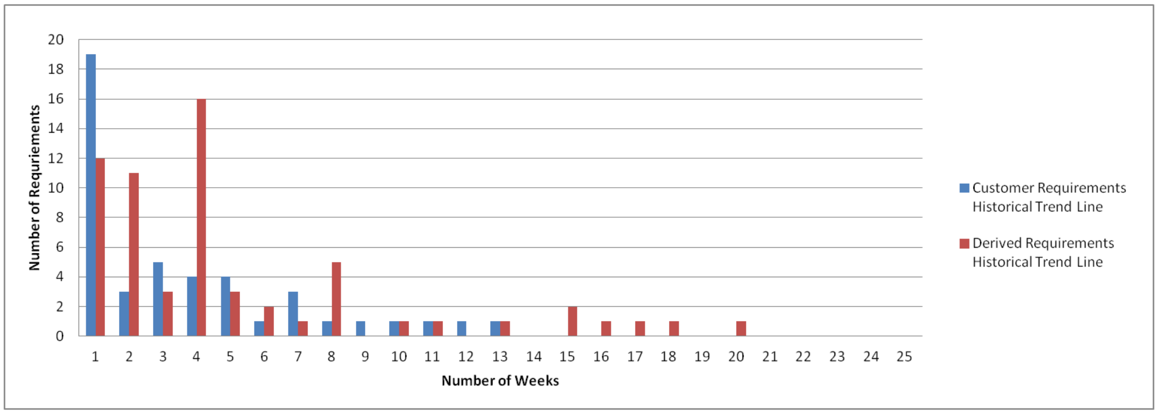


Figure 43: Requirements Validation Rate Derived Measure

The data, using the second equation, suggests that the majority of customer requirements should be validated within five weeks of obtaining the requirement, and no customer requirement should take more than 13 weeks (Figure 44). Derived requirement should not take more than 20 weeks to be validated (Figure 45). The historical data also suggest that derived requirements take longer to validate than customer requirements. The historical data had an average total number of 45 customer requirements and 62 derived requirements. The ideal project trend line would be above the historical trend.

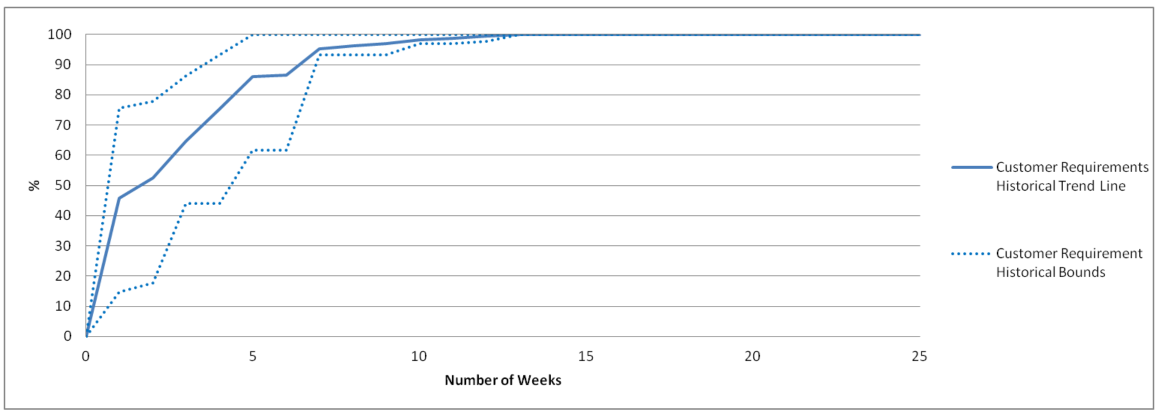


Figure 44: Customer Requirements Validation Rate Historical Trend Lines

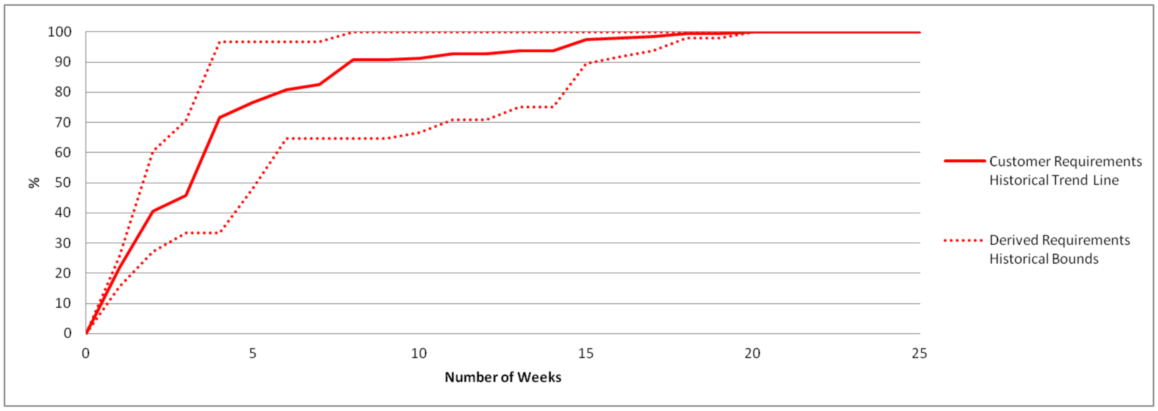


Figure 45: Derived Requirements Validation Rate Historical Trend Lines

By week 30, 60 percent into the project timeline, all 11 of Project A’s requirements had been validated. Of these 11 requirements, six are customer requirements and five are derived requirements. The customer requirements took five, six and 10 weeks, respectively, to be validated and the trend line stayed within the historical bounds 60 percent of the time for the 25 weeks (Figure 46). The project’s derived requirements took six, eight and 15 weeks, respectively, to be validated and the trend line stayed within the historical bounds 40 percent of the time for the 25 weeks (Figure 47). For both types of requirements the project trend lines are below the historical trend lines and the historical bounds until all the project lines reach 100 percent. Even though the data shows the trend lines within the bounds 60 percent and 40 percent of the 25 weeks, the amount of time it is taking to validate requirements is longer than historically shown. The data indicates an unstable project and the PM should investigate as to why it is taking longer than normal for the requirements to be validated.

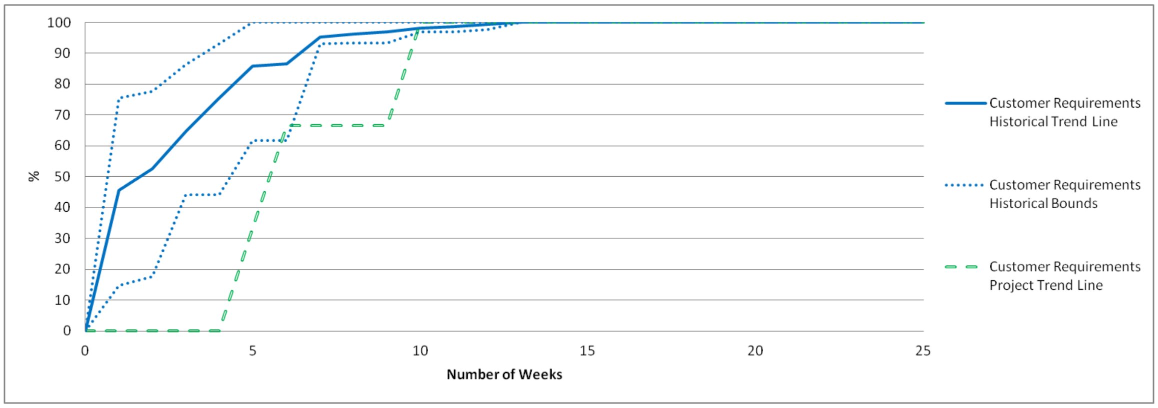


Figure 46: Project A Customer Requirements Validation Rate Trend Lines

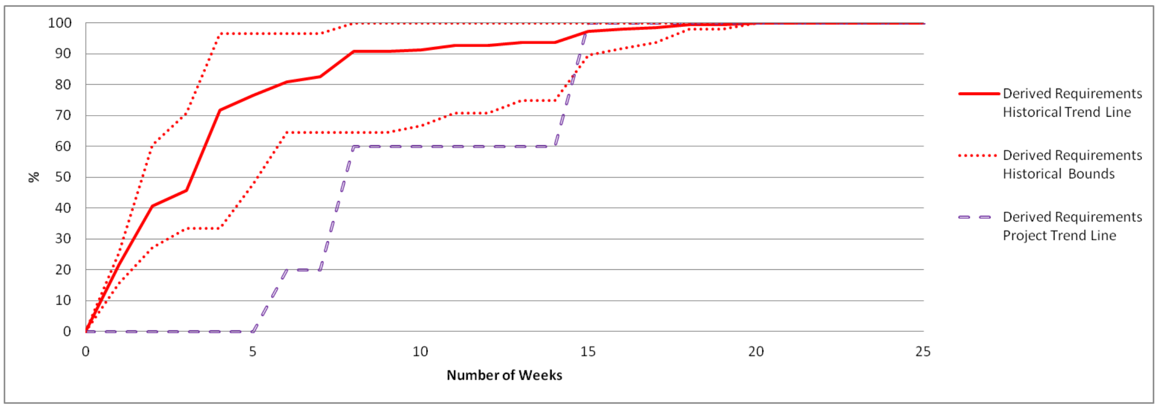


Figure 47: Project A Derived Requirements Validation Rate Trend Lines

Project B had more requirements recorded than Project A. Out of the 26 recorded requirements, 16 were customer requirements and ten were derived requirements. By week 12, 60 percent into the project timeline, 15 of the customer requirements and eight of the derived requirements were approved. The customer requirements took two, four, six, eight, nine and ten weeks, respectively (Figure 48). The derived requirements took four and nine weeks, respectively, to be validated (Figure 49). The customer requirements fell within the historical bounds 60 percent of the time and derived requirements trend lines fell within the historical bounds 64 percent of the time for the 25 weeks. Similarly to Project A, both types of requirements trend lines are below the historical trend lines, and even though the data show the trend lines within the bounds over 60 percent of the 25 weeks, the amount of time it is taking to validate requirements is longer than historically shown. The data indicates an unstable project, and the PM should investigate why it is taking longer than normal for the requirements to be validated.

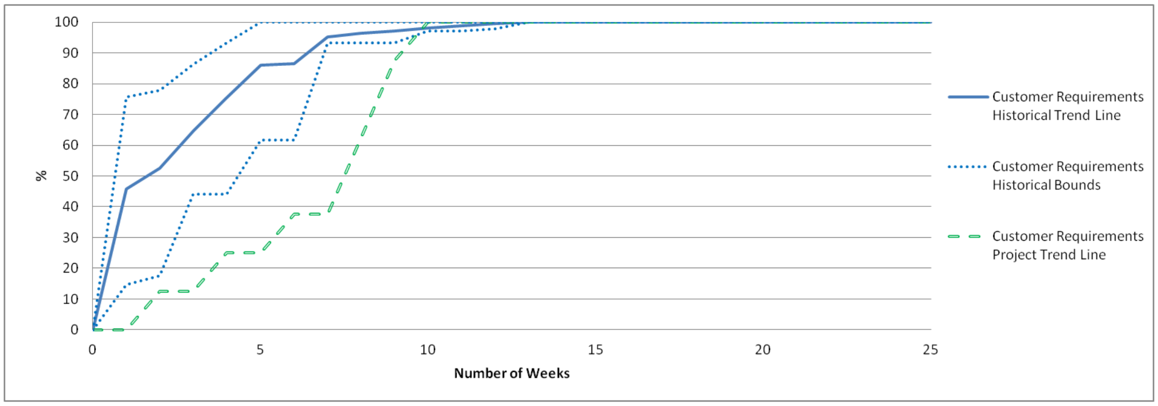


Figure 48: Project B Customer Requirements Validation Rate Trend Lines

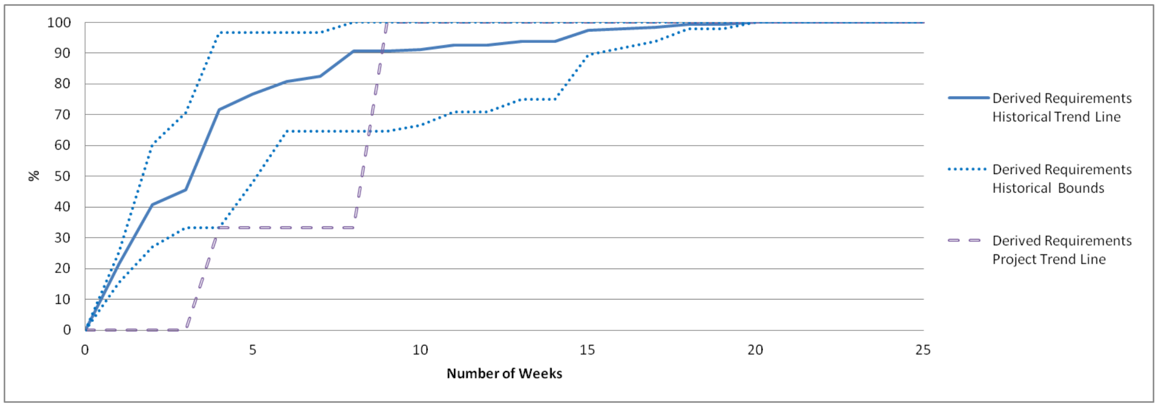


Figure 49: Project B Derived Requirements Validation Rate Trend Lines

With a total number of 42 requirements, Project C comes closest to the amount of requirements from the historical information out of the three projects; however, the length of the project is the shortest. Twenty-two of the requirements are customer requirements and 20 are derived requirements. By week 11, 78 percent into the project timeline, 18 of the customer requirements and 11 of the derived requirements were validated. The customer requirements took one through three weeks to be validate and the derived requirements took one through four weeks to be validate (Figures 50 & 51). The customer requirements stay within the bounds 96 percent of the 25 weeks and the derived requirements stayed within bounds 72 percent of the 25 weeks. The customer requirements start inside the requirements historical bounds and continue to increase until they exceeded the bounds. The derived requirements start above the requirements historical bounds and remain near the top of the historical bound or above only going inside the bounds by 15 percent. Unlike the previous two projects, this data shows Project B is stable.

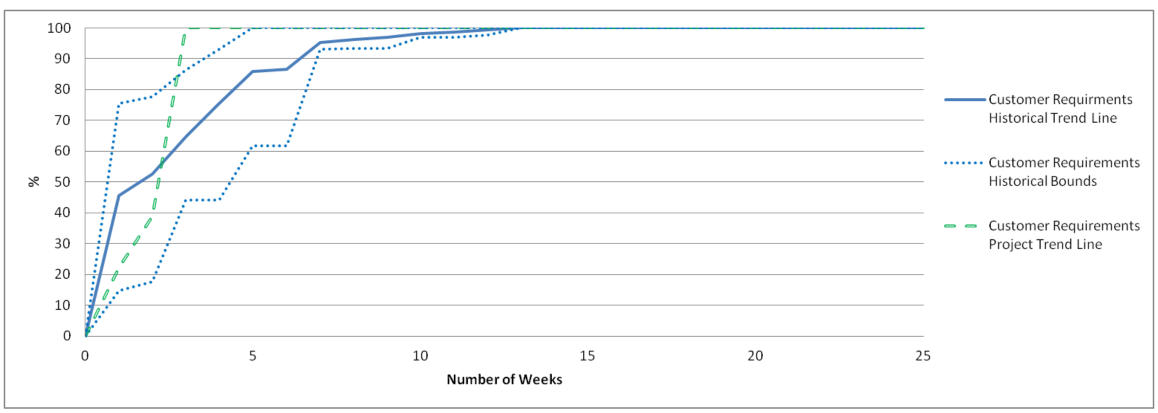


Figure 50: Project C Customer Requirements Validation Rate Trend Lines

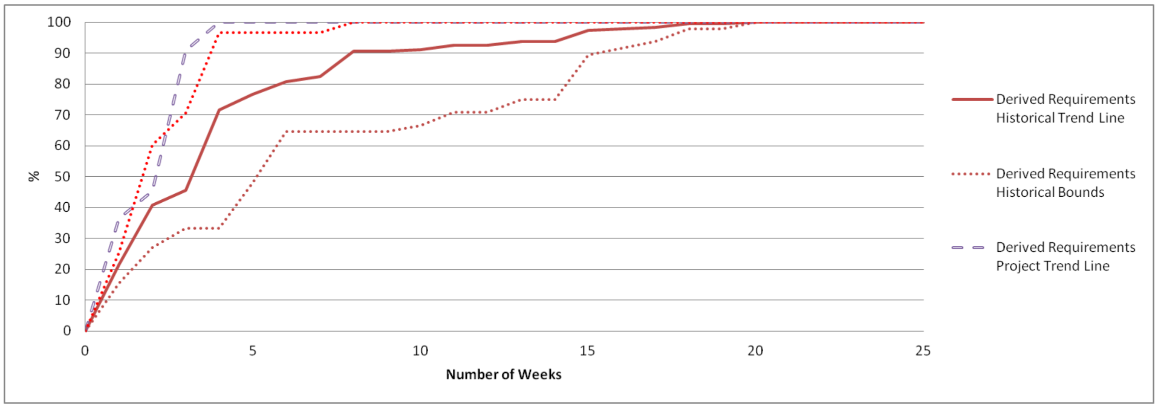


Figure 51: Project C Derived Requirements Validation Rate Trend Lines

Out of all three projects, Project C was the only one that came close to fitting the historical lines. One reason for this is that Project C has the most recorded requirements and the closest to the amount of recorded requirements in the historical data. Another reason for only one out of the three projects matching the historical trends is that this derived measure only took into account the length of time it took for a requirement to be validated and not the length of the project or the number of requirements. More research needs to be conducted for this derived measure. The effect of the different project lengths needs to be researched along with the difference in the number of requirements. Project length and amount of requirements should be scaled.

Percent Requirements Validated Derived Measures

The trend lines for the percent requirements validated derived measure are percentages graphed over time. This derived measure takes into account the number of validated requirements versus the total number of requirements and uses the equation:

$$\left(\frac{requirements\ validated}{total\ number\ of\ requirements}\right) \times 100$$

The historical trend lines suggest that no less than 13 percent of customer requirements and 25 percent of derived requirements should be validated at any point during the project (Figures 52 & 53). By the time the project is 50 percent complete, both types of requirements should be no less than 60 percent validated, and by the time the project is 75 percent complete all of the requirements should be validated. The historical bound for the customer requirements is very wide for most of the project with a maximum lower difference of 39 percent and maximum upper difference of 42 percent. In contrast, the historical bound for the derived requirements is narrower with maximum lower difference of 16 percent and maximum upper difference of 29 percent. For this derived measure, having the project trend lines above the historical trend lines is a positive outcome. Having the project trend lines below the historical trend lines is a negative outcome. The PM needs to examine why requirements are not being validated and to determine if action needs to be taken to ensure the requirements are being validated in a timely manner.

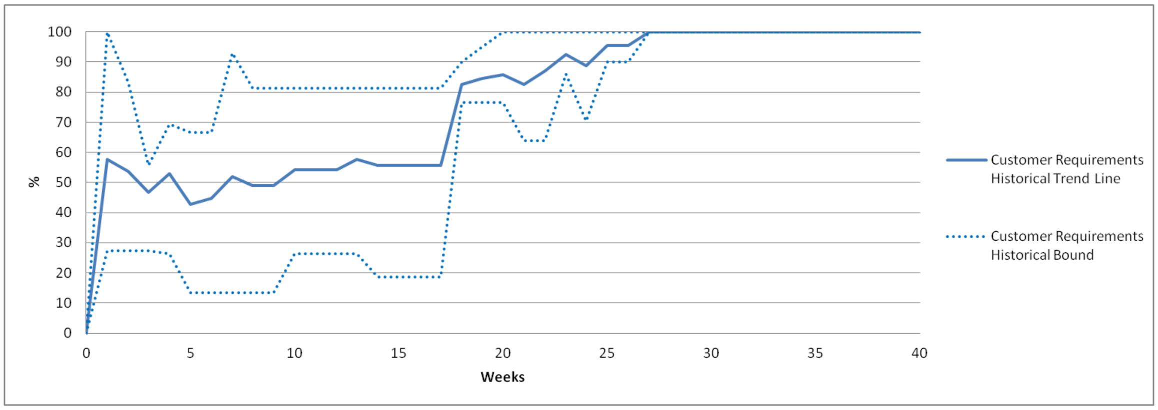


Figure 52: Percent Customer Requirements Validated Historical Trend Line

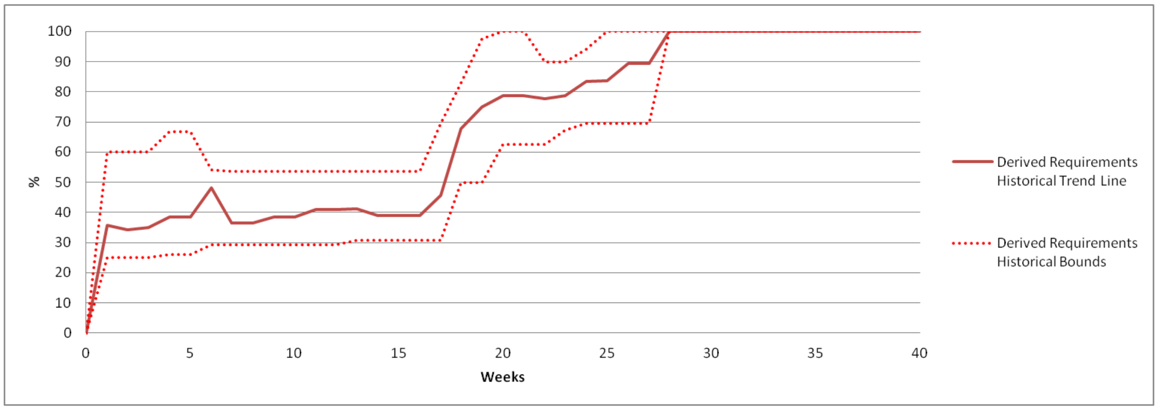


Figure 53: Percent Derived Requirements Validated Historical Trend Line

Project A's customer requirements trend line start within the historical bounds and continue to grow until it exceeds the bounds (Figure 54). It only stays within the bounds for 56 percent of the project. However, this is not a negative outcome for the project. The project trend does not follow the historical norm but instead shows a better result. The derived requirements trend does not start within the historical bounds and is only within the bounds 17 percent of the project (Figure 55). For the first eight weeks, the project line is no less than 25 percent under the lower historical bound and barely rises above the lower bound by four percent in week 10. The PM should be very concerned about the time it is taking to validate the derived requirements until week 16 when the project line shift sharply upwards above the upper historical bound.

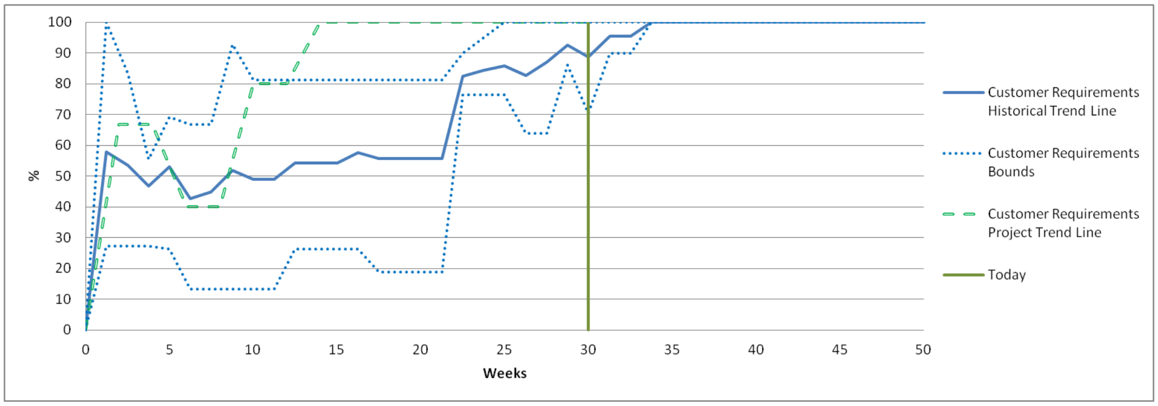


Figure 54: Project A Percent Customer Requirements Validated Trend Lines

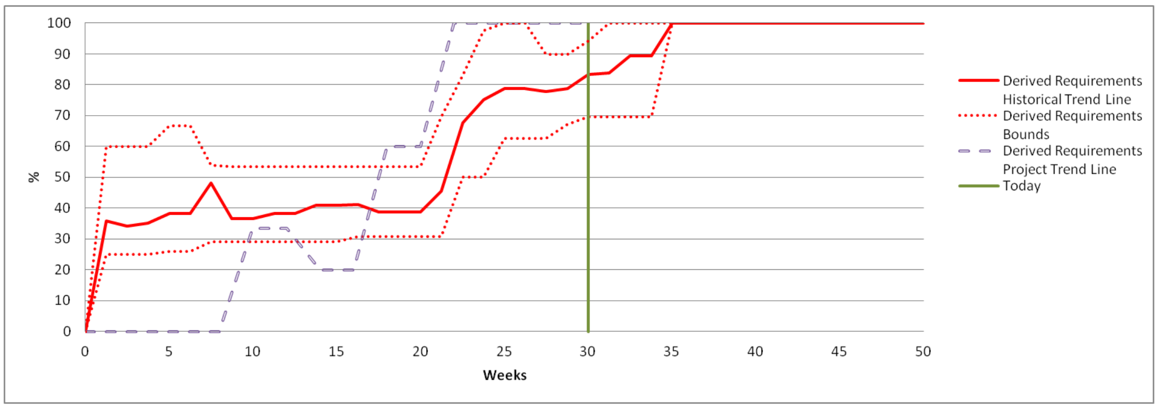


Figure 55: Project A Percent Derived Requirements Validated Trend Lines

Project B's trend lines match the percent requirements validated derived measure trend lines fairly well (Figures 56 & 57). For the majority of the project, the project trend lines are slightly above the historical trend lines and stay within the historical bounds. The customer requirements trend line stays within the bound for 92 percent of the project, and the derived requirements trend line stays within the bounds for 58 percent of the project. At week ten, when the project trend lines fall below the historical trend lines, the PM should not be overly concerned about the direction of the trend. The derived requirements project trend line is still within the historical bounds, and the customer requirements project trend line is only 6 percent below the historical bound and has an upward trend. This is proven by week 12, when the trend lines match with the historic trend lines.

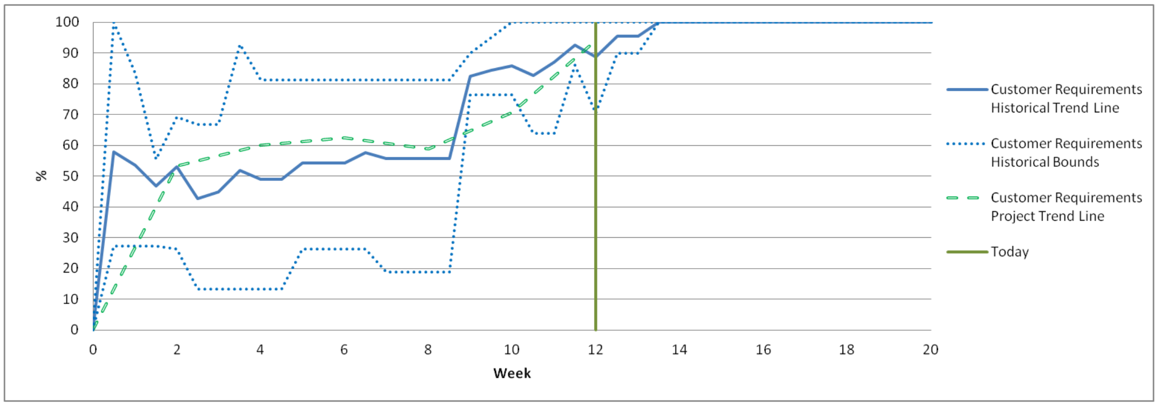


Figure 56: Project B Percent Customer Requirements Validated Trend Lines

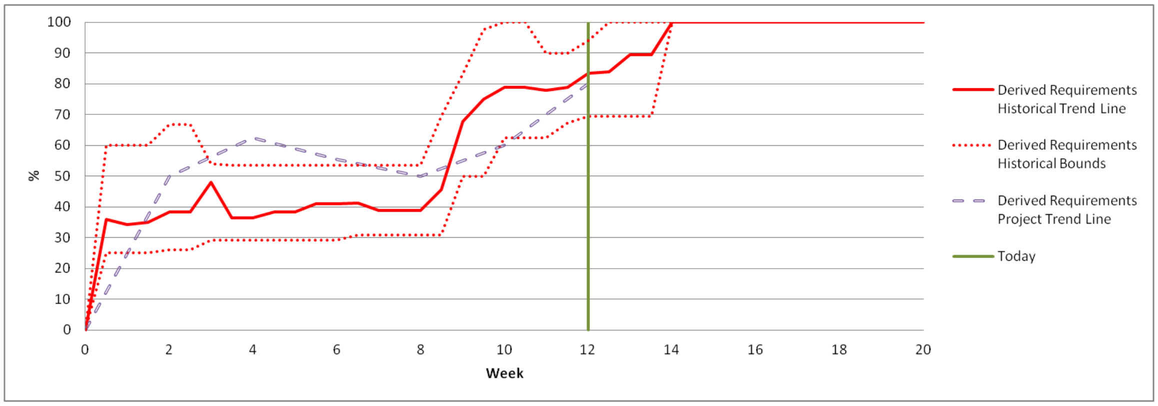


Figure 57: Project B Percent Derived Requirements Validated Trend Lines

Project C's customer requirements trend line stays within the historical bounds for 64 percent of the project (Figure 58). After week nine, when not all of the customer requirements have been validated, the PM should be concerned and investigate. Project C's derived requirements trend line does not stay within the bounds and instead remains below the lower bound (Figure 59). The spike on the graph at week three should be considered an anomaly and be ignored. This spike links back to the percent requirements growth derived measure when the project's requirements jumped by 23 percent in week four creating new requirements which needed to be validated.

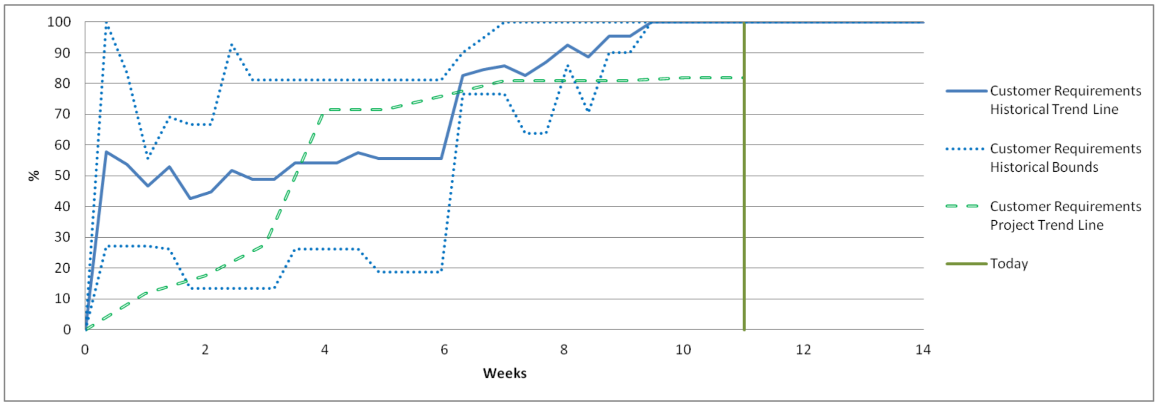


Figure 58: Project C Percent Customer Requirements Validated Trend Lines

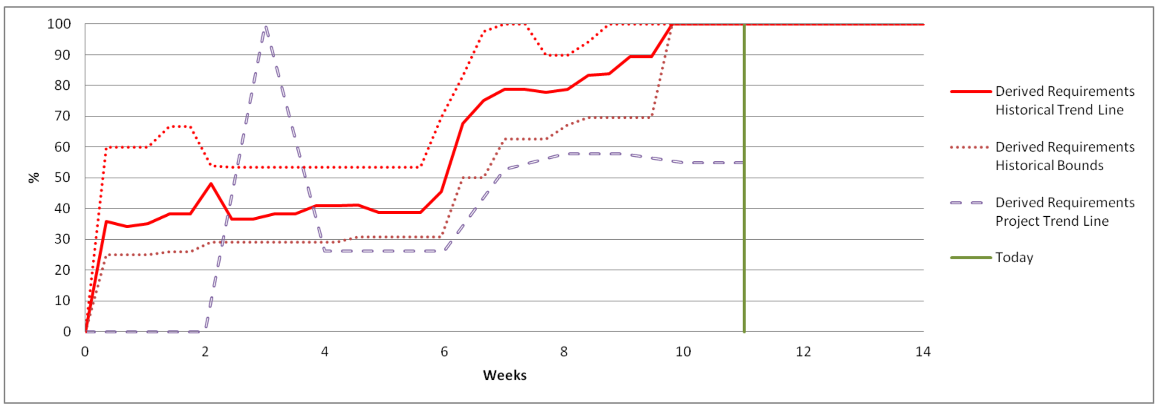


Figure 59: Project C Percent Derived Requirements Validated Trend Lines

Project B's trend lines were the closest out of the three projects to match the historical trend lines and stay within the historical bounds. On the other hand, Project A and C's derived requirement trend lines were not close to the historical trend line and, for the majority of the projects, did not stay within the historical bounds.

Summary

By conducting research and applying results from a questionnaire, the top three SE processes for a high speed sled track environment were determined. These three SE processes include requirements management, risk management and technical planning. Using these findings and a second questionnaire, the top three LI trends for a high speed sled track environment were determined. These three LI trends include requirements, requirements validation, and facility and equipment availability. From the top three LI trends, requirements and requirements validation trends were chosen to be broken down and the current and historical project trends compared.

From the two LI trends, seven derived measures were chosen to obtain historical and project data to be analyzed: percent requirements approved, percent requirements growth, percent requirements TBD/TBR closure variance per plan, percent requirement modified, estimated impact of requirements change, requirements validation rate, and percent requirements validated. Each of the derived measures is unique. Obtaining information from these derived measures gives an understanding of how a project is going to be effective in the future. The historical bounds used for this thesis are the maximum and the minimum historical values for each collection interval. If these historical bounds are overly wide, as shown in the percent requirement growth derived measure, the historical projects do not agree for that derived measure and information obtain is not reliable.

For the majority of the derived measures, the project trend lines did not match the historical trend lines. Thirty percent of the project trend lines were located within the historical trend for over 70 percent of the project, 30 percent of the project trend lines were located within the historical bounds between 40 percent and 60 percent of the project and 40 percent of the project trend lines were located within the historical bounds for less than 39 percent of the project (Figure 60). There could be many reasons for the discrepancy between the current projects and historical trend lines. Among these reasons are the number of requirements being tracked by the PM, the communication between the PM and the customer, the length of the projects, and the fact that no project is truly the same as another.

Derived Measure	Project A		Project B		Project C	
	Customer Requirement	Derived Requirement	Customer Requirement	Derived Requirement	Customer Requirement	Derived Requirement
Percent Requirements Approved	50%	57%	67%	50%	45%	0%
Percent Requirements Growth	83%	0%	0%	0%	0%	0%
Percent Requirements TBD/TBR Closure Variance per Plan	17%	7%	83%	33%	73%	36%
Percent Requirements Modified	0%	0%	100%	100%	100%	100%
Estimated Impact of Requirements Change	0%		100%		100%	
Requirements Validation Rate	60%	40%	60%	64%	96%	72%
Percent Requirements Validated	56%	17%	92%	58%	64%	0%

% Within Historical Bounds
70% - 100%
40% - 69%
0% - 39%

Figure 60: Percent of Time Project Lines were Inside of Historical Bounds

A project trend line not lying within the historical bounds does not automatically constitute a negative outcome. This only means the project is not following what has historically happened. In some cases not following the historical trend or staying within the historical bounds is a positive outcome. A good example is Project A's customer requirements trend for the percent requirements TBD/TBR closure variance derived measure. The project's trend line is within the historical bounds for only 17 percent of the project, but the project receives no requirements that need TBD or TBR which is a very positive outcome for the project.

For the information obtained from the different LI trends to be interpolated properly, the user, normally a PM or Systems Engineer, must be familiar with the project or system. These trend lines are only showing part of the story

V. Conclusions and Recommendations

Chapter Overview

This chapter will cover the results of determining which SE activities the sled track community currently emphasizes and uses, which LI trends are most relevant to a sled track environment; how current trend lines compare to historical trend lines; and which of the suggested derived measures are relevant to a sled track environment. Recommendations on how to proceed in future research will also be discussed in this chapter.

Conclusions of Research

The *DAG* describes 16 key SE processes that should be utilized during a project. By researching HHSTT project notes, SOIs and various project meeting minutes, it was determined that of the 16 processes, only six were being utilized at the HHSTT: requirements management, risk management, interface management, stakeholder requirements definition, verification and validation processes. A questionnaire was given to members of the HHSTT regarding which processes were most useful to them. In the first part of the questionnaire, members of the HHSTT rated the top processes. The top processes were selected by their average rating. These top processes included: technical planning, requirements management, risk management, decision analysis and technical assessment. In the second part of the questionnaire, members of the HHSTT ranked the entire group of processes as to usefulness. The top processes were selected by their average ranking and included: requirements management, technical planning, risk management and data management. Combining information gathered from research and the questionnaire, the top three most useful SE processes in the sled track community are requirements management, risk management and technical planning processes.

All of the 16 SE processes link to at least one of the LI trends. The six currently utilized SE processes link to 15 LI trends. These trends include requirements, systems definition change backlog, requirements validation, requirements verification, work product approval, review action closure, risk exposure, risk treatment, technical measurement, systems engineering staffing and skill, process compliance, facility and equipment availability, defect/error, system affordability, and schedule and cost pressure. Taking into account information gathered from the SE process questionnaire, the number of linked LI trends drops to ten. These trends include requirements, work product approval, review action closure, risk exposure, risk treatment, systems engineering staffing and skill, processes compliance, facility and equipment availability, defect/error, and scheduled cost pressure. A second questionnaire was given to members of the HHSTT regarding which LI trends were thought to be most useful. The first part of the questionnaire rated each of the 18 LI trends as to their individual usefulness. The top LI trends were selected by their average rating. The top LI trends were identified as: requirements, requirements validation, facility and equipment availability, and requirements verification. The second part of the questionnaire ranked each of the 18 LI trends as a group to their usefulness. The top LI trends were selected by their average ranking and included: requirements, requirements validation, facility and equipment availability, and requirements verification. Combining the information obtained from the SE processes research and the LI trends questionnaire, the top three most relevant LI trends for a sled track environment are requirements, facility and equipment availability, and requirements validation.

The requirements trend and the requirements validation trend were chosen to conduct project and historical trend research. Both of the LI trends were broken down into their suggested derived measures. Five out of the nine suggested derived measures for the requirements trend were used, and both of the suggested derived measures for the requirements validation trend were used. Overall, the current project trends did not match the historical trends. Thirty percent of the project trend lines were located within the historical trend for over 70 percent of the project; 30 percent of the project trend lines were located within the historical bounds between 40 percent and 60 percent of the project; and 40 percent of the project trend lines were located within the historical bounds less than 39 percent of the project. There could be many reasons behind the discrepancy between current project and historical trend lines. Among these reasons are the number of requirements being tracked by the PM, the communication between the PM and the customer, the length of the projects and the fact that no project is truly the same as another.

A project trend line not lying within the historical bounds does not automatically constitute a negative outcome. This only means the project is not following what has historically happened. In some cases, not following the historical trend or staying within the historical bounds is a positive outcome. For the information obtained from the different LI trends to be interpolated properly, the user, normally a PM or Systems Engineer, must be familiar with the project or system. These trend lines are only showing part of the story. The correct type and number of LI trends and derived measures need to be chosen. The correct collection interval also needs to be determined. There must be a balance between the amount and type of information collected, the amount of effort put into the data collection, and the type and size of project or system.

Significance of Research

SE is utilized at very low levels in the sled track community and in most cases not emphasized at all. The use of LI introduces a tool to help promote the use of SE and help change the mindset of the usefulness of SE in the testing community. One of the reasons SE is being used at relatively low levels is the lack of confidence in the SE process and resistance to change. This thesis has shown that SE is currently being utilized in the sled track environment even though the sled track does not promote its use or even recognize the degree to which they are currently using SE. This thesis also demonstrates that there are LI trends relevant to the high speed sled track community and that by utilizing these trends during a project the sled track can contribute valuable knowledge about a sled test project to improve the outcome of the project.

Recommendations for Future Research

More research should be conducted on LI trends not only in the sled test community but also in the testing community as a whole. Data was only collected from the HHSTT, and only two LI trends were broken down into their derived measures. Data should be collected from other sled tracks as well as from other organizations within the testing community. Additional LI trends should also be researched and broken down at multiple testing organizations. Comparing the results from different testing organizations will give a more complete picture of which SE actives the testing community emphasizes, values and uses along with what LI trends the testing community finds most relevant.

Three very different projects were used in this study to obtain a wide range of data. Project A is a 50 week project which consists of 11 top level requirements, Project B is a 40 week project which consists of 25 top and medium level requirements, and Project C is a 14 week project which consists of 42 requirements from all levels. Future research should be conducted with more similar projects to determine if there is a link between the usefulness of a LI trend and the number of requirements or the length of the project.

Summary

This research effort focused on applying the SE processes through the use of LI trends to a sled track testing environment to determine if the use of LI trends can help improve project progress and outcomes. The first step determined the top SE processes for a high speed test track environment. They were then linked to the LI trends to help determine the top LI trends. Two LI trends were then chosen to be applied to three sled track test projects at the HHSTT. The last step was a comparison of the historical trend lines to project trend lines.

It is hoped that through this research of application of the LI trends, the HHSTT will continue to utilize LI trends and place more emphasis on the SE processes during their projects.

Appendix A

Leading Indicator Measurement Specifications

{Name of Leading Indicator}	
Information Need Description	
Information Need	*Specifies what the information need is that drives why we need this leading indicator to make decisions*
Information Category	*Specifies what categories (as defined in the PSM) are applicable for this leading indicator (for example, schedule and progress, resources and cost, product size and stability, product quality, process performance, technology effectiveness, and customer satisfaction)*
Measurable Concept and Leading Insight	
Measurable Concept	*Defines specifically what is measurable*
Leading Insight Provided	*Specifies what specific insights that the leading indicator may provide in context of the measurable concept - typically a list of several or more*
Base Measure Specification	
Base Measures	*A list of the base measures that are used to compute one or more leading indicators - a base measure is a single attribute defined by a specified measurement method*
Measurement Methods	*For each base measure, describes the method used to count the base measure, for example simple counting or counting then normalized*
Unit of Measurement	*Describes the unit of measure for each of the base measures*
Entities and Attributes	
Relevant Entities	*Describes one or more particular entities relevant for this indicator – the object is to be measured (for example, requirement or interface)*
Attributes	*Lists the subset of particular attributes (characteristics or properties) for each entity that are of interest for this leading indicator*
Derived Measure Specification	
Derived Measure	*Describes one or more measures that may be derived from base measures that will be used individually or in combination as leading indicators*
Measurement Function	*The function for computing the derived measure from the base measures*
Indicator Specification	
Indicator Description and Sample	*A detailed specific description and display of the leading indicator, including what base and/or derived measures are used*
Thresholds and Outliers	*Would describe thresholds and outliers for the indicator; this information would be company (and possibly project) specific*
Decision Criteria	*Provides basic guidance for triggers for investigation and when possible action to be taken*
Indicator Interpretation	*Provides some insight into how the indicator should be interpreted; each organization would be expected to tailor this*

Additional Information

{Name of Leading Indicator}	
Related Processes	*Lists related processes and sub-processes*
Assumptions	*Lists assumptions for the leading indicator to be used, for example, that a requirements database is maintained*
Additional Analysis Guidance	*Any additional guidance on implementing or using the indicators*
Implementation Considerations	*Considerations on how to implement the indicator (assume this expands with use by organization)*
User of Information	*Lists the role(s) that use the leading indicator information*
Data Collection Procedure	*Details the procedure for data collection*
Data Analysis Procedure	*Details the procedure for analyzing the data prior to interpretation*

Data Collection Procedure (for each Base Measure) *Complete this section for each base measure listed in each measurement information specification*	
Frequency of Data Collection	Collect at least monthly; more frequently during peak activity periods. Do not sample - collect all requirements data.
Responsible Individual	Measurement Analyst, Requirements Manager, Configuration Management Manager
Activity in which Collected	From concept and system definition through system deployment
Potential Sources of Data	Requirements Database, Change Board records, defect data
Typical Tools Used in Data Collection	Requirement Database, Configuration Management Database
Verification and Validation	Check data against Configuration Management records.
Repository for Collected Data	User defined.
Data Analysis Procedure (for each Indicator)	
Frequency of Data Reporting	Biweekly to monthly, depending on the level of activity
Responsible Individual	Measurement Analyst
Activity in which Analyzed	From concept and system definition through system deployment
Source of Data for Analysis	Requirements Database, Change Board records, defect data
Tools Used in Analysis	Spreadsheet, statistical analysis, measurement analysis
Review, Report, or User	Chief SE, Product Manager.

Appendix B

System Engineering Processes Questionnaire

On the attached page there is a list of 16 system engineering processes and a brief description according to the Defense Acquisition Handbook. These processes are used to help keep a program on schedule and under budget. Sled track projects are very unique and do not always follow the typical DoD format. Please look at each process individually and rank them 1 to 5 on how useful they would be for a sled test project, with 1 being the most useful. Now look at them as a group and rank them 1 to 16 with 1 being the most useful process for a sled test project.

Processes	**Rank Individually 1 -5**	**Rank as a Group 1-16**
Decision Analysis Process	________	________
Technical Planning Process	________	________
Technical Assessment Process	________	________
Requirements Management Process	________	________
Risk Management Process	________	________
Configuration Management Process	________	________
Data Management Process	________	________
Interface Management Process	________	________
Stakeholder Requirements Definition Process	________	________
Requirements Analysis Process	________	________
Implementation Process	________	________
Integration Process	________	________
Verification Process	________	________
Validation Process	________	________
Transition Process	________	________

System Engineering Processes

Processes	**Description**
Decision Analysis Process	Provides the basis for evaluating alternatives and selecting the optimum decision.
Technical Planning Process	Provides the critical quantitative input to program planning and ensures the systems engineering processes are applied properly throughout the system's life cycle.
Technical Assessment Process	Measures technical progress and assesses both program plans and requirements
Requirements Management Process	Provides traceability back to user-defined capabilities as documented through either the Joint Capabilities Integration and Development System or other user-defined source, and to other sources of requirements.
Risk Management Process	Overarching process that encompasses identification, analysis, mitigation planning, mitigation plan implementation, and tracking.
Configuration Management Process	Establishes and controls product attributes and the technical baseline across the total system lifecycle.
Data Management Process	Applies Policies, procedures and information technology to plan for, acquire access, manage, protect, and use data of a technical nature to support the total life cycle of the system.
Interface Management Process	Ensures interface definition and compliance amount the elements that compose the system, as well as with other systems with which the system or system elements will interoperate.
Stakeholder Requirements Definition Process	Elicits inputs from relevant stakeholders and translates the inputs into technical requirements.
Requirements Analysis Process	Provides measureable and verifiable requirements.
Implementation Process	Yields the lowest level system elements in the system hierarchy. The elements that will be combined together to create the full system.
Integration Process	Incorporates the lower level system elements into a higher-level system element in the physical architecture.
Verification Process	Confirms that the system element meets the design to or build-to specifications as defined in the functional, allocated, and product baselines.
Validation Process	Answers the question of "Is it the right solution to the problem?"
Transition Process	Moves any system element to the next level in the physical architecture.

* Reference: Defense Acquisition University. 2011. *Defense Acquisition Guidebook*.

Appendix C

Leading Indicator Questionnaire

On the attached page there is a list of 18 leading indicator trends and a brief description. These trends are used to help give insight into the direction a project is going and whether or not corrective action needs to be taken. Please look at each trend individually and rank them 1 to 5 on how useful they would be for a sled test project, with 1 being the most useful. Now look at them as a group and rank them 1 to 18 with 1 being the most useful trend for a sled test project.

Trend	**Rank Individually 1-5**	**Rank as a Group 1-18**
Requirements	______	______
System Definition Chase Log	______	______
Interface	______	______
Requirements Validation	______	______
Requirements Verification	______	______
Work Product Approval	______	______
Review Action Closure	______	______
Risk Exposure	______	______
Risk Handling	______	______
Technology Maturity	______	______
Technical Measurement	______	______
System Engineering Staffing & Skill	______	______
Process Compliance	______	______
Facility and Equipment Availability	______	______
Defect and Error	______	______
System Affordability	______	______
Architecture	______	______
Schedule and Cost Pressure	______	______

Leading Indicators

Trend	Description
Requirements	Rate of maturity of the system definition against the plan. Also characterizes stability and completeness of system requirements which could potentially impact design and production.
System Definition Chase Backlog	Change request backlog which, when excessive, could have adverse impact on the technical, cost and schedule baselines.
Interface	Interface specification closure against plan. Lack of timely closure could pose adverse impact to system architecture, design, implementation and/or V&V any of which could pose technical, cost and schedule impact.
Requirements Validation	Progress against plan is assuring that the customer requirements are valid and properly understood. Adverse trends would pose impacts to system design and activity with corresponding impacts to technical, cost & schedule baseline and customer satisfaction.
Requirements Verification	Progress against plan is verifying that the design meets the specified requirements. Adverse trends would indicate inadequate design and rework that could impact technical, cost and schedule baselines. Also, potential adverse operational effectiveness of the system.
Work Product Approval	Adequacy of internal processes from the work being performed and also the adequacy of the document review process, both internal and external to the organization. High reject count would suggest poor quality work or a poor document review process each of which could have adverse cost, schedule and customer satisfaction impact.
Review Action Closure	Responsiveness of the organization in closing post-review actions. Adverse trends could forecast potential technical, costs and schedule baseline issues.
Risk Exposure	Effectiveness of risk management process in managing / mitigating technical, cost & schedule risks. An effective risk handling process will lower risk exposure trends.
Risk Handling	Effectiveness of SE organization in implementing risk mitigation activities. If the SE organization is not retiring risk in a timely manner, additional resources can be allocated before additional problems are created.

Technology Maturity	Risk associated with incorporation of new technology or failure to refresh dated technology. Adoption of immature technology could introduce significant risk during development while failure to refresh dates technology could have operational effectiveness / customer satisfaction impact.
Technical Measurement	Progress towards meeting the Measures of Effectiveness, Measures of Performance, Key Performance Parameters and Technical Performance Measures. Lack of timely closure is an indicator of performance deficiencies in the product design and / or project team's performance.
Systems Engineering	Ability of SE organization to execute total SE program. Includes quantity of SE personnel
Staffing & Skill	assigned, the skill and seniority mix and the time phasing of their application throughout the program lifecycle.
Process Compliance	Quality and consistency of the project defined SE process. Poor / inconsistent SE processes and / or failure to adhere to the SE process increase program risk.
Facility and Equipment Availability	Availability of critical facilities and equipment needed. Composed of two metrics, one type that measures facility availability and the other that measures equipment availability.
Defect and Error	Amount of defects and errors over time for the project. A defect is a deviation of a product at any stage of its development, implementation, or operation from its requirements or applicable standards.
System Affordability	The estimate of the cost of the system at the end of the project with a given confidence and the customer's ability or willingness to pay that price for the project's deliverables.
Architecture	The progress that an engineering team is making towards developing a comprehensive system architecture.
Schedule and Cost Pressure	The impact of schedule and cost challenges to the execution of the project. The percentage differences between project estimates and contracted values.

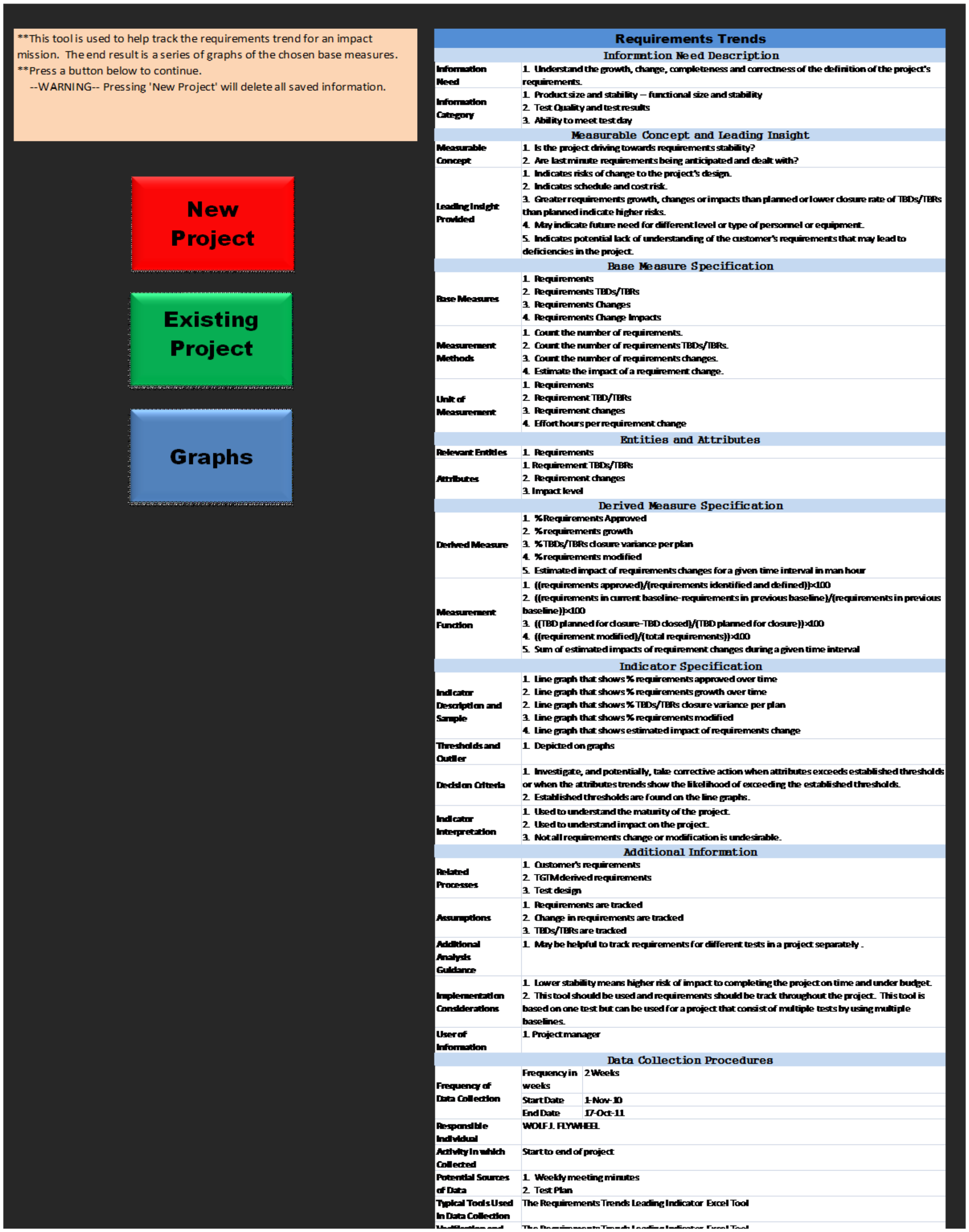
* Reference: Rhodes, Valerdi, and Roedler. 2008. *Systems Engineering Leading Indicators for Assessing Program and Technical Effectiveness*.
*Reference: Roedler, Rhodes, Schimmoller, Jones. 2010. Systems Engineering Leading Indicators Guide, Version 2.0.

Appendix D

Leading Indicator Excel Tool

To collect information from the HHSTT two tools were created, one for each of the chosen LI trends. The tools utilize Microsoft Excel and are written using Visual Basic for Applications (VBA). The user chooses what data and trend lines they would like to track, they enter their data and the program computes a graphic containing the LI trend information from historical data and the user's project's data.

The tools are split into four page categories: the Start Page, Project Input page, Derived Measures Input pages and Results Page. The start page (Figure 61) utilizes the LI measurement specifications chart (Appendix A) from the 'Systems Engineering Leading Indicators Guide, Version 2.0' to display the LI trend characteristics. This chart is updated with user inputs from the Project Input page. From the Start page the user has the options to start a new project, open the exiting project or go directly to the results page. The new project button will erase all prior user inputs and bring up the Project Input page. The exiting project button will keep all prior user inputs and bring up the Project Input page. The Graph button will bring up the results page. The program is designed to always open to this page.



Requirements Trends	
Information Need Description	
Information Need	1. Understand the growth, change, completeness and correctness of the definition of the project's requirements.
Information Category	1. Product size and stability – functional size and stability 2. Test Quality and test results 3. Ability to meet test day
Measurable Concept and Leading Insight	
Measurable Concept	1. Is the project driving towards requirements stability? 2. Are last minute requirements being anticipated and dealt with?
Leading Insight Provided	1. Indicates risks of change to the project's design. 2. Indicates schedule and cost risk. 3. Greater requirements growth, changes or impacts than planned or lower closure rate of TBDs/TBRs than planned indicate higher risks. 4. May indicate future need for different level or type of personnel or equipment. 5. Indicates potential lack of understanding of the customer's requirements that may lead to deficiencies in the project.
Base Measure Specification	
Base Measures	1. Requirements 2. Requirements TBDs/TBRs 3. Requirements Changes 4. Requirements Change Impacts
Measurement Methods	1. Count the number of requirements. 2. Count the number of requirements TBDs/TBRs. 3. Count the number of requirements changes. 4. Estimate the impact of a requirement change.
Unit of Measurement	1. Requirements 2. Requirement TBD/TBRs 3. Requirement changes 4. Effort hours per requirement change
Entities and Attributes	
Relevant Entities	1. Requirements
Attributes	1. Requirement TBDs/TBRs 2. Requirement changes 3. Impact level
Derived Measure Specification	
Derived Measure	1. %Requirements Approved 2. %requirements growth 3. %TBDs/TBRs closure variance per plan 4. %requirements modified 5. Estimated impact of requirements changes for a given time interval in man hour
Measurement Function	1. ((requirements approved)/(requirements identified and defined))×100 2. ((requirements in current baseline-requirements in previous baseline)/(requirements in previous baseline))×100 3. ((TBD planned for closure-TBD closed)/(TBD planned for closure))×100 4. ((requirement modified)/(total requirements))×100 5. Sum of estimated impacts of requirement changes during a given time interval
Indicator Specification	
Indicator Description and Sample	1. Line graph that shows % requirements approved over time 2. Line graph that shows % requirements growth over time 2. Line graph that shows % TBDs/TBRs closure variance per plan 3. Line graph that shows % requirements modified 4. Line graph that shows estimated impact of requirements change
Thresholds and Outlier	1. Depicted on graphs
Decision Criteria	1. Investigate, and potentially, take corrective action when attributes exceeds established thresholds or when the attributes trends show the likelihood of exceeding the established thresholds. 2. Established thresholds are found on the line graphs.
Indicator Interpretation	1. Used to understand the maturity of the project. 2. Used to understand impact on the project. 3. Not all requirements change or modification is undesirable.
Additional Information	
Related Processes	1. Customer's requirements 2. TGTM derived requirements 3. Test design
Assumptions	1. Requirements are tracked 2. Change in requirements are tracked 3. TBDs/TBRs are tracked
Additional Analysis Guidance	1. May be helpful to track requirements for different tests in a project separately .
Implementation Considerations	1. Lower stability means higher risk of impact to completing the project on time and under budget. 2. This tool should be used and requirements should be track throughout the project. This tool is based on one test but can be used for a project that consist of multiple tests by using multiple baselines.
User of Information	1. Project manager
Data Collection Procedures	
Frequency of Data Collection	Frequency in weeks: 2 Weeks Start Date: 1-Nov-10 End Date: 17-Oct-11
Responsible Individual	WOLF J. FLYWHEEL
Activity in which Collected	Start to end of project
Potential Sources of Data	1. Weekly meeting minutes 2. Test Plan
Typical Tools Used in Data Collection	The Requirements Trends Leading Indicator Excel Tool

Figure 61: LI Tool Start Page

The Project Input pages (figure 62 & 63) are where the user chooses what they would like to track and how often. The first input is who the Project Manger (PM) is for this project. The second input is what is being tracked. Each LI trend is broken down into their derived measures. The requirements trend has five derived measures to choose from; percent of requirements approved, percent of requirements growth, percent of requirements TBD/TBR, percent of requirements modified and estimated affected hours. The requirements validation trend has two derived measures to choose from; requirements validation rate and percent requirements validated. The next two input sections are data collection and data reporting. The user enters the frequency of the data collection/reporting in weeks, the start data of the collection/reporting and the estimated number of collections/reports for the project. The program calculates the end date. The number of collections/reports can be updated at any point in the project, in turn updating the end date, to accommodate changes in the length of the project. A typical project's data collection and data reporting will be the same; however for the rare occasion when they are different the tool lists them separately. The inputs from this page are transferred to the LI measurement specification chart on the Start page. The next button formats each of the Derived Measures Input pages and brings up the first Derived Measures Input page that has been selected. Any derived measure that had not been selected will not be displayed while transitioning through the tool.

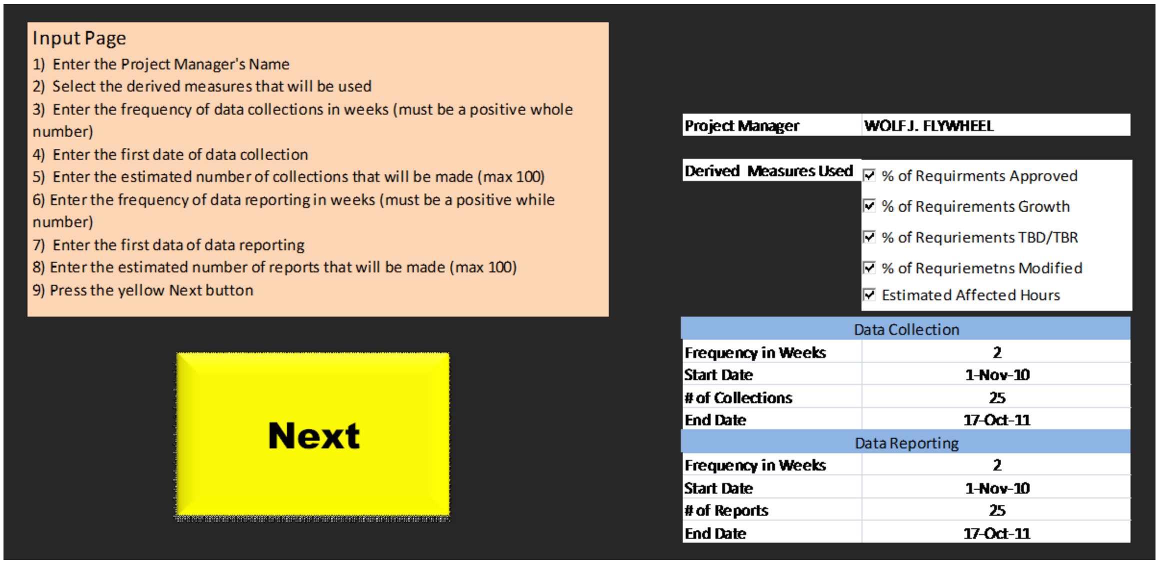


Figure 62: Requirements Trend Project Input Page

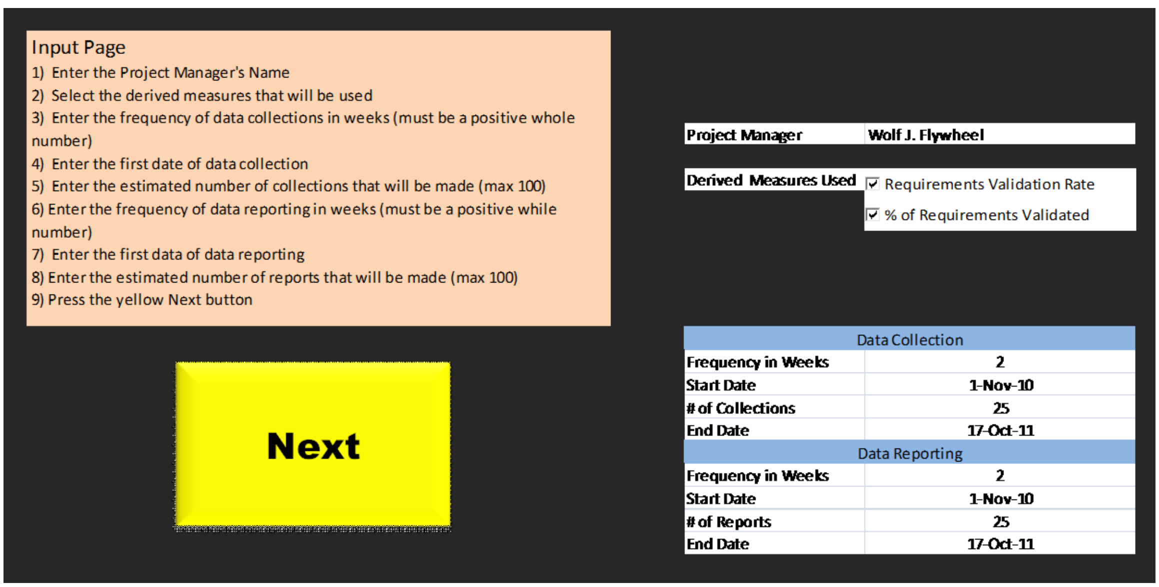
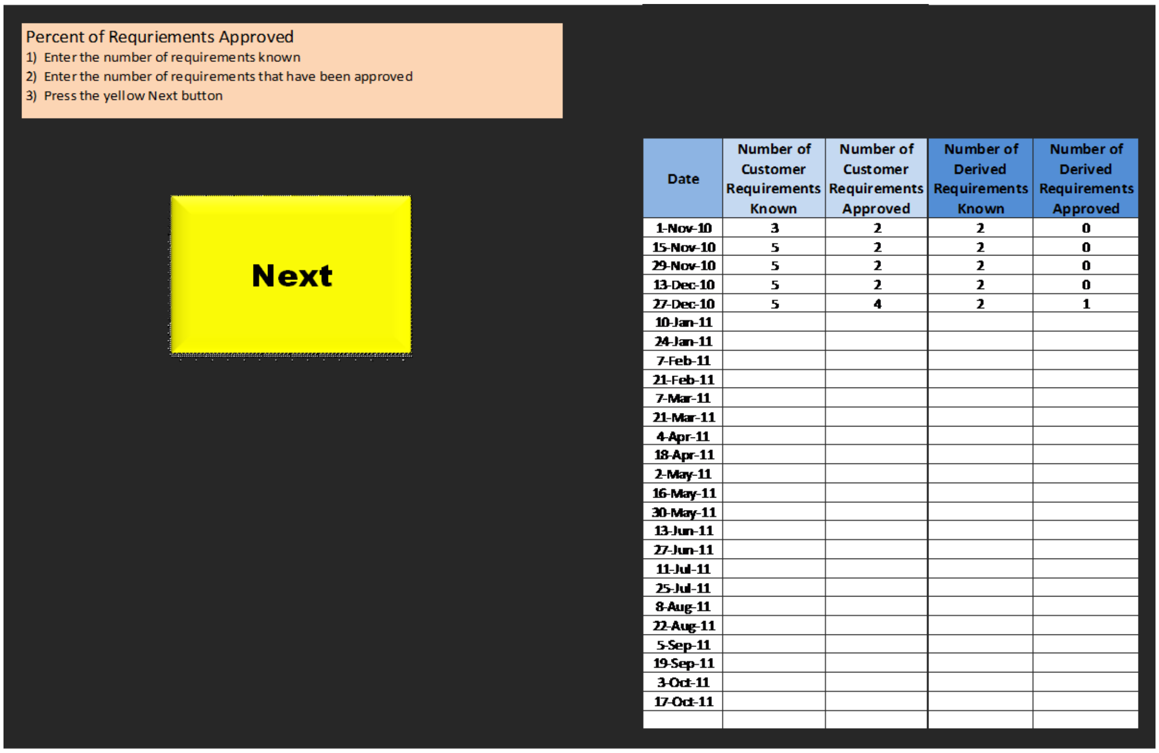


Figure 63: Requirements Validation Trend Project Input Page

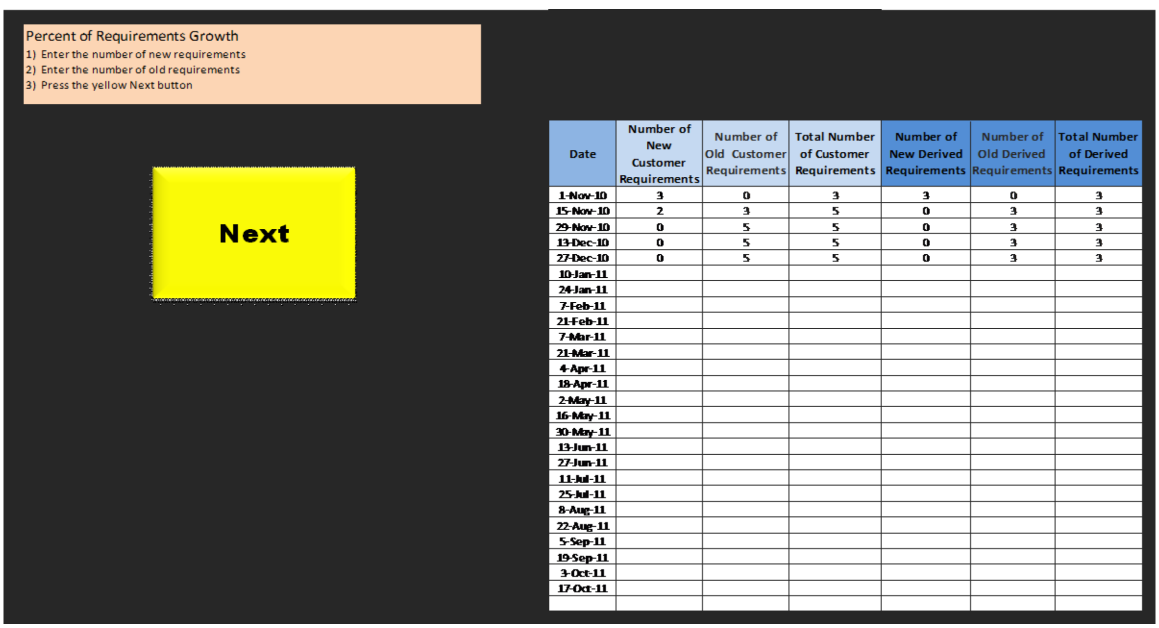
The Derived Measures Input pages are configured for the user to input the required data next to their respected date. The dates are preset on the page from the data imputed on the Project Input page. The tool completes any calculations needed simplifying the input process for the user. The Next button brings up the next Derived Measures Input page. When all Derived Measures Input pages have been viewed the last Next button brings up the Results page.

Within the requirements trend tool the Percent of Requirements Approved Input page (Figure 64) allows the user to enter the number of known requirements and the number of requirements that have been approved. The Percent of Requirements Growth Input page (Figure 65) allows the user to enter the number of new requirements. The tool calculates the number of old requirements and the total number of requirements from previous inputs. The Percent of Requirements TBD/TBR Input page (Figure 66) allows the user to enter the number of requirements TBD/TBR open and the number of requirements TBD/TBR closed. The tool calculates the total number of requirements that are or have been TBD/TBR. The Percent of Requirements Modified Input page (Figure 67) allows the user to enter the total number of requirements and the number of the requirements modified. The Estimated Affected Hours Input page (Figure 68) allows the user to enter the additional hours needed to complete the project due to requirements changes or late requirements for that collection period. The tool calculates the previous additional work hours and the total number of additional work hours needed to complete the project to date.



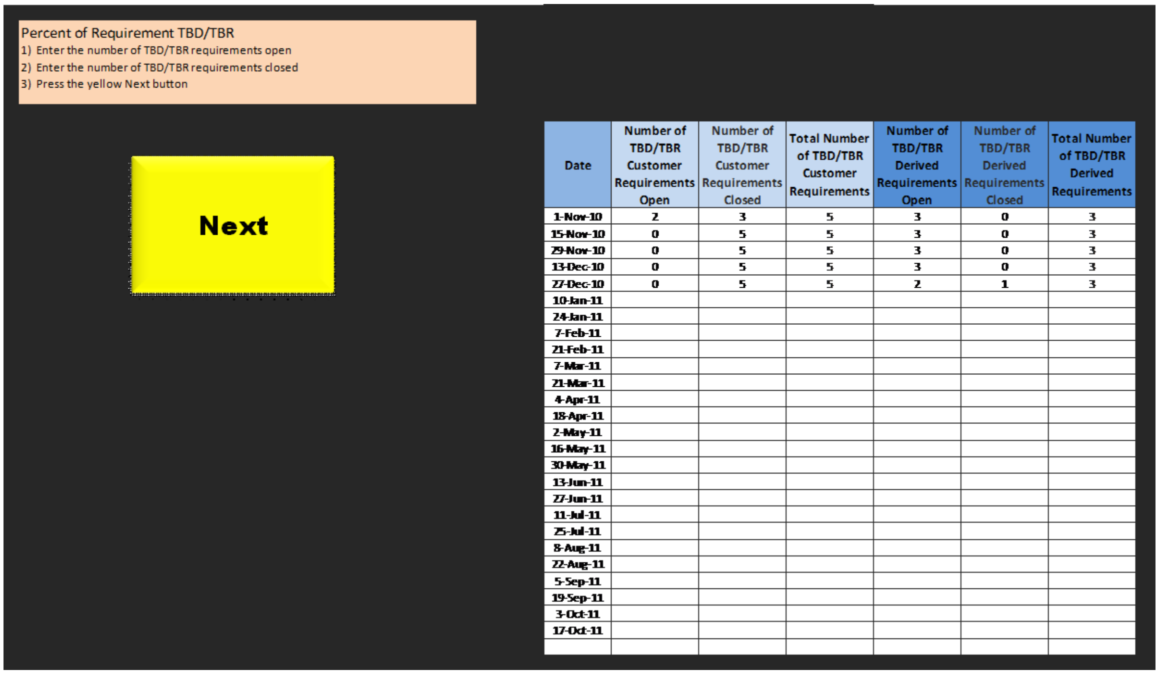
Date	Number of Customer Requirements Known	Number of Customer Requirements Approved	Number of Derived Requirements Known	Number of Derived Requirements Approved
1-Nov-10	3	2	2	0
15-Nov-10	5	2	2	0
29-Nov-10	5	2	2	0
13-Dec-10	5	2	2	0
27-Dec-10	5	4	2	1
10-Jan-11				
24-Jan-11				
7-Feb-11				
21-Feb-11				
7-Mar-11				
21-Mar-11				
4-Apr-11				
18-Apr-11				
2-May-11				
16-May-11				
30-May-11				
13-Jun-11				
27-Jun-11				
11-Jul-11				
25-Jul-11				
8-Aug-11				
22-Aug-11				
5-Sep-11				
19-Sep-11				
3-Oct-11				
17-Oct-11				

Figure 64: Percent of Requirements Approved Input Page



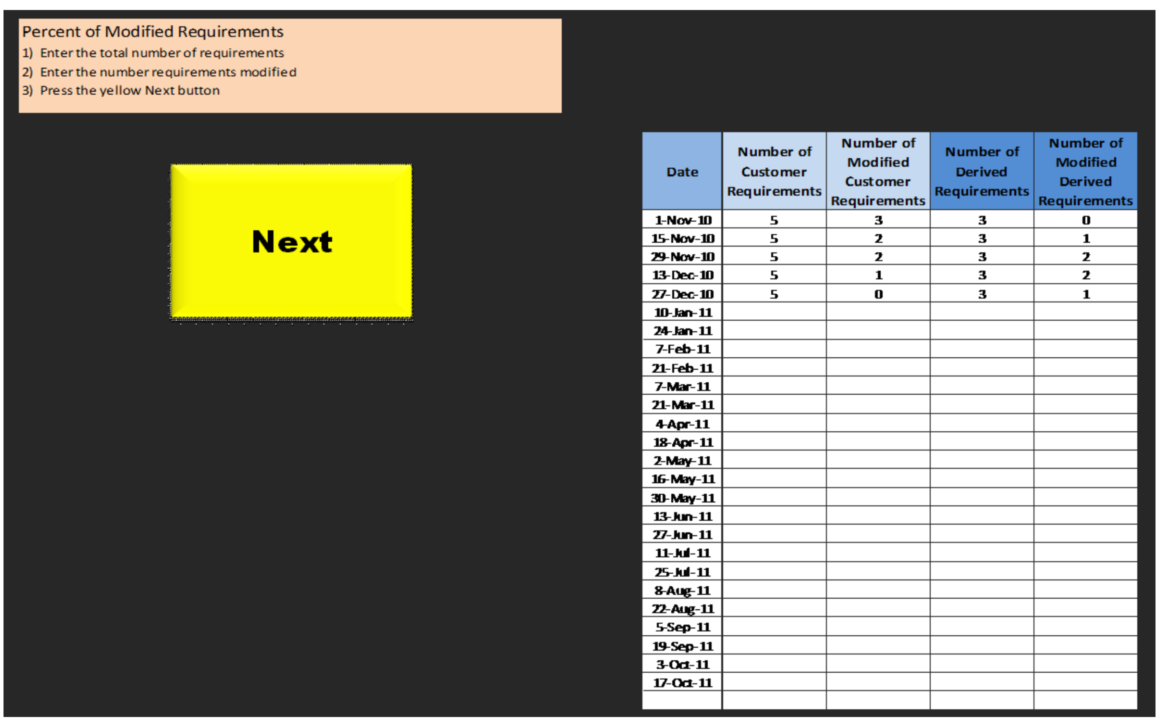
Date	Number of New Customer Requirements	Number of Old Customer Requirements	Total Number of Customer Requirements	Number of New Derived Requirements	Number of Old Derived Requirements	Total Number of Derived Requirements
1-Nov-10	3	0	3	3	0	3
15-Nov-10	2	3	5	0	3	3
29-Nov-10	0	5	5	0	3	3
13-Dec-10	0	5	5	0	3	3
27-Dec-10	0	5	5	0	3	3
10-Jan-11						
24-Jan-11						
7-Feb-11						
21-Feb-11						
7-Mar-11						
21-Mar-11						
4-Apr-11						
18-Apr-11						
2-May-11						
16-May-11						
30-May-11						
13-Jun-11						
27-Jun-11						
11-Jul-11						
25-Jul-11						
8-Aug-11						
22-Aug-11						
5-Sep-11						
19-Sep-11						
3-Oct-11						
17-Oct-11						

Figure 65: Percent of Requirements Growth Input Page



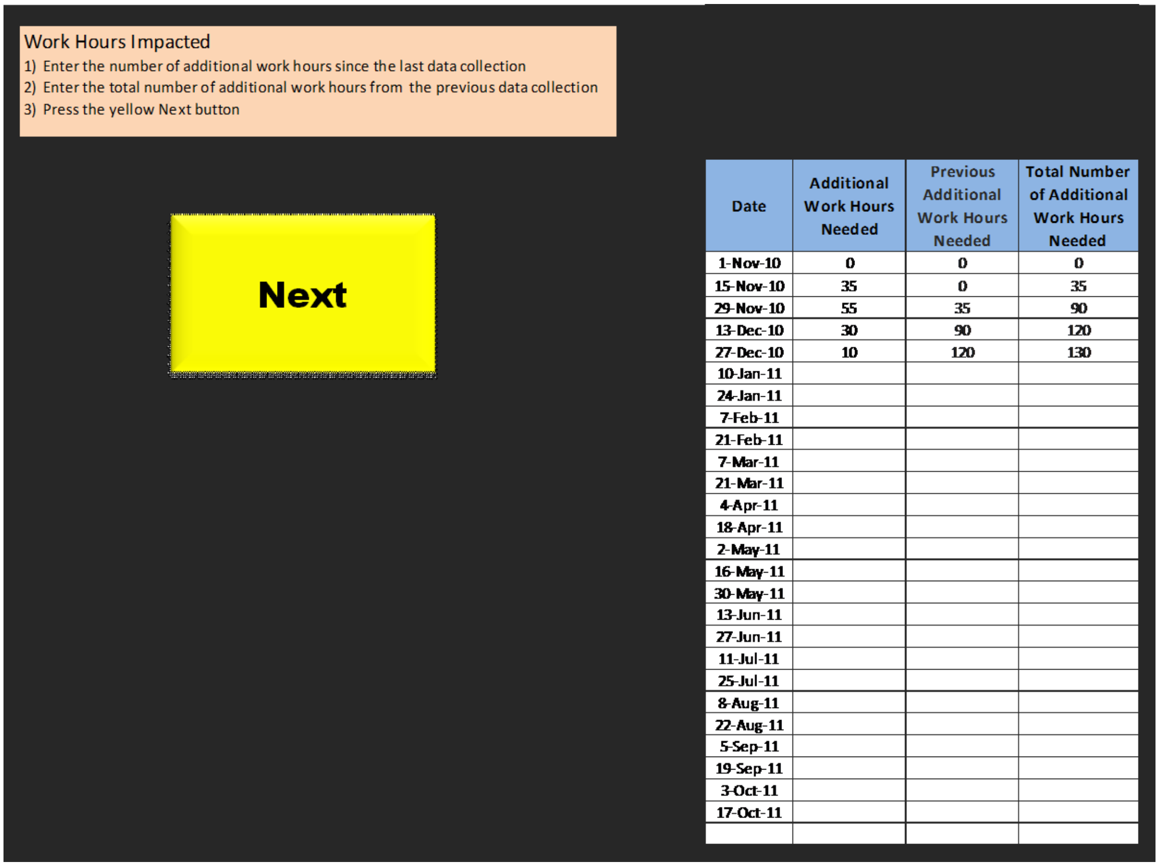
Date	Number of TBD/TBR Customer Requirements Open	Number of TBD/TBR Customer Requirements Closed	Total Number of TBD/TBR Customer Requirements	Number of TBD/TBR Derived Requirements Open	Number of TBD/TBR Derived Requirements Closed	Total Number of TBD/TBR Derived Requirements
1-Nov-10	2	3	5	3	0	3
15-Nov-10	0	5	5	3	0	3
29-Nov-10	0	5	5	3	0	3
13-Dec-10	0	5	5	3	0	3
27-Dec-10	0	5	5	2	1	3
10-Jan-11						
24-Jan-11						
7-Feb-11						
21-Feb-11						
7-Mar-11						
21-Mar-11						
4-Apr-11						
18-Apr-11						
2-May-11						
16-May-11						
30-May-11						
13-Jun-11						
27-Jun-11						
11-Jul-11						
25-Jul-11						
8-Aug-11						
22-Aug-11						
5-Sep-11						
19-Sep-11						
3-Oct-11						
17-Oct-11						

Figure 66: Percent of Requirements TBD/TBR Input Page



Date	Number of Customer Requirements	Number of Modified Customer Requirements	Number of Derived Requirements	Number of Modified Derived Requirements
1-Nov-10	5	3	3	0
15-Nov-10	5	2	3	1
29-Nov-10	5	2	3	2
13-Dec-10	5	1	3	2
27-Dec-10	5	0	3	1
10-Jan-11				
24-Jan-11				
7-Feb-11				
21-Feb-11				
7-Mar-11				
21-Mar-11				
4-Apr-11				
18-Apr-11				
2-May-11				
16-May-11				
30-May-11				
13-Jun-11				
27-Jun-11				
11-Jul-11				
25-Jul-11				
8-Aug-11				
22-Aug-11				
5-Sep-11				
19-Sep-11				
3-Oct-11				
17-Oct-11				

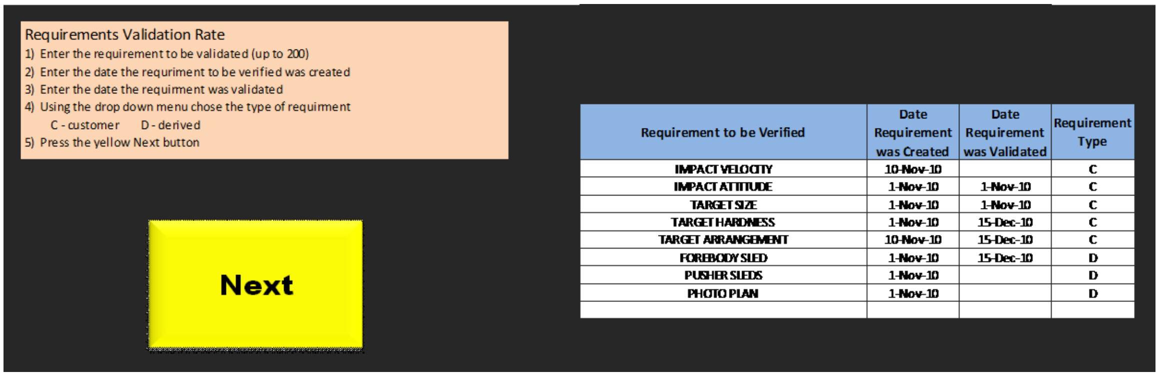
Figure 67: Percent of Requirements Modified Input Page



Date	Additional Work Hours Needed	Previous Additional Work Hours Needed	Total Number of Additional Work Hours Needed
1-Nov-10	0	0	0
15-Nov-10	35	0	35
29-Nov-10	55	35	90
13-Dec-10	30	90	120
27-Dec-10	10	120	130
10-Jan-11			
24-Jan-11			
7-Feb-11			
21-Feb-11			
7-Mar-11			
21-Mar-11			
4-Apr-11			
18-Apr-11			
2-May-11			
16-May-11			
30-May-11			
13-Jun-11			
27-Jun-11			
11-Jul-11			
25-Jul-11			
8-Aug-11			
22-Aug-11			
5-Sep-11			
19-Sep-11			
3-Oct-11			
17-Oct-11			

Figure 68: Estimated Affected Hours Input Page

Within the requirements validation tool the Requirements Validation Rate page allows the user to list all the project requirements with the date the requirement was created and the date the requirement was validated (Figure 69). A drop down menu allows the user to choose the type of requirement, C for customer or D for derived. The Percent of Requirements Verified page allows the user to enter the total number of requirements and the total number of requirements that have been verified (Figure 70).

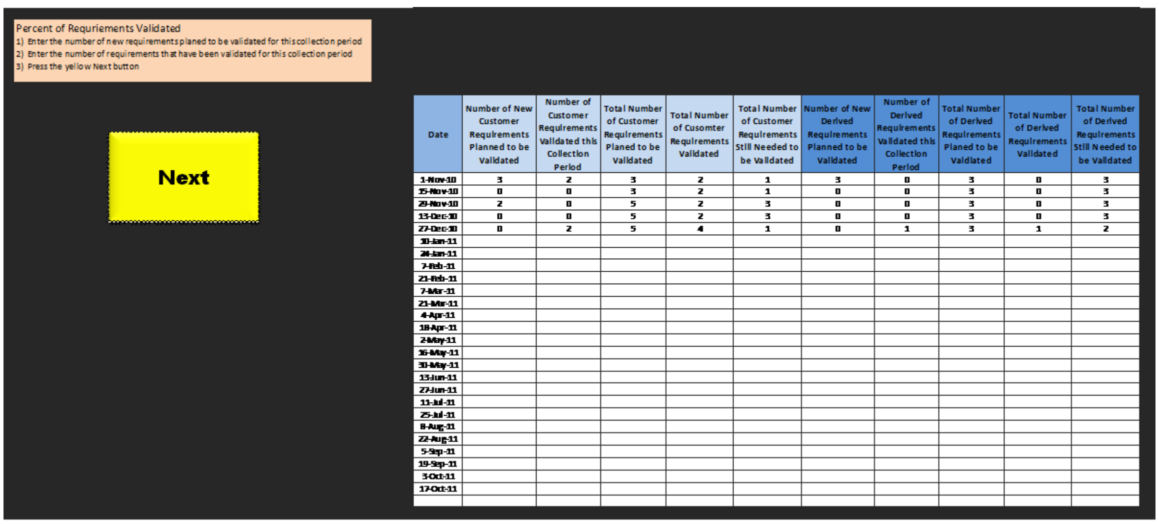


Requirements Validation Rate
1) Enter the requirement to be validated (up to 200)
2) Enter the date the requirment to be verified was created
3) Enter the date the requirment was validated
4) Using the drop down menu chose the type of requirment
C - customer D - derived
5) Press the yellow Next button

Next

Requirement to be Verified	Date Requirement was Created	Date Requirement was Validated	Requirement Type
IMPACT VELOCITY	10-Nov-10		C
IMPACT ATTITUDE	1-Nov-10	1-Nov-10	C
TARGET SIZE	1-Nov-10	1-Nov-10	C
TARGET HARDNESS	1-Nov-10	15-Dec-10	C
TARGET ARRANGEMENT	10-Nov-10	15-Dec-10	C
FOREBODY SLED	1-Nov-10	15-Dec-10	D
PUSHER SLEDS	1-Nov-10		D
PHOTO PLAN	1-Nov-10		D

Figure 69: Requirements Validation Rate Input Page



Percent of Requriements Validated
1) Enter the number of new requirements planed to be validated for this collection period
2) Enter the number of requirements that have been validated for this collection period
3) Press the yellow Next button

Next

Date	Number of New Customer Requirements Planned to be Validated	Number of Customer Requirements Validated this Collection Period	Total Number of Customer Requirements Planed to be Validated	Total Number of Cusomter Requirements Validated	Total Number of Customer Requirements Still Needed to be Validated	Number of New Derived Requirements Planned to be Validated	Number of Derived Requirements Validated this Collection Period	Total Number of Derived Requirements Planed to be Valdiated	Total Number of Derived Requirements Validated	Total Number of Derived Requirements Still Needed to be Validated
1-Nov-10	3	2	3	2	1	3	0	3	0	3
15-Nov-10	0	0	3	2	1	0	0	3	0	3
29-Nov-10	2	0	5	2	3	0	0	3	0	3
13-Dec-10	0	0	5	2	3	0	0	3	0	3
27-Dec-10	0	2	5	4	1	0	1	3	1	2
10-Jan-11										
24-Jan-11										
7-Feb-11										
21-Feb-11										
7-Mar-11										
21-Mar-11										
4-Apr-11										
18-Apr-11										
2-May-11										
16-May-11										
30-May-11										
13-Jun-11										
27-Jun-11										
11-Jul-11										
25-Jul-11										
8-Aug-11										
22-Aug-11										
5-Sep-11										
19-Sep-11										
3-Oct-11										
17-Oct-11										

Figure 70: Percent of Requirements Validated Input Page

The Results page shows the tools output in form of graphs (figure 71 & 72). Each derived measure has a separate graph. The graphs for the derived measures that were not chosen will be blank. All of the graphs are line graphs except for the requirements validation rate derived measure which is a bar graph. The graphs contain a historical trend line and a project trend line. The tool scales the historical trend line to match the length of the chosen project. They also contain a vertical line depicting the current date.

The user uses these graphs and their knowledge of the project and organization to make informed decisions about the project and whether or not the corrected actions need to be made. The Save Project button opens the save as function, the Edit Project button takes the user to the Inputs page and the Start Page button takes the user to the Start page.

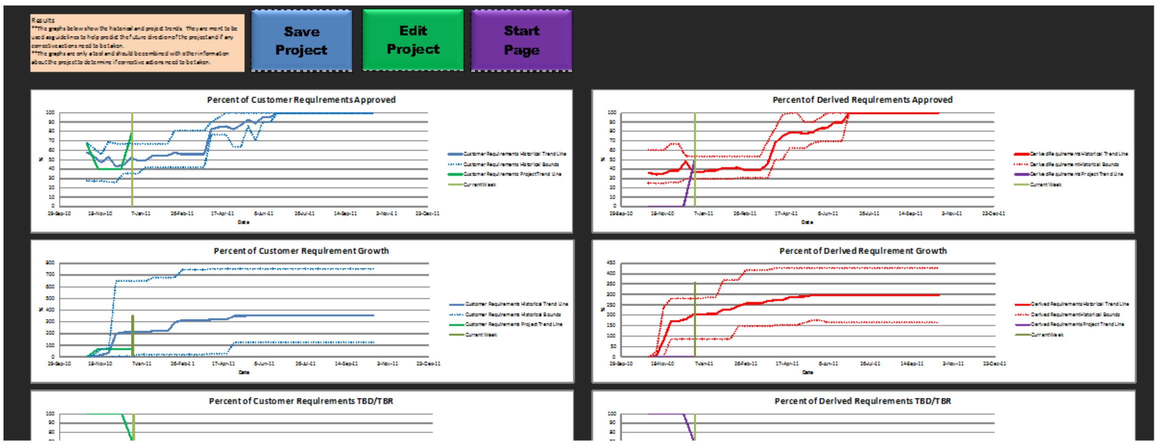


Figure 71: Requirements Trend Results Page

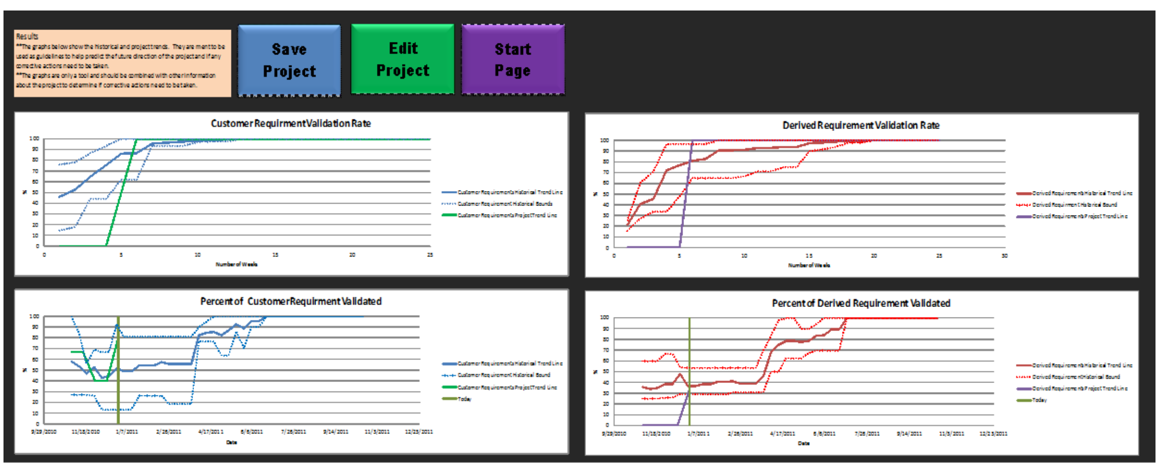


Figure 72: Requirements Validation Trend Results Page

This tool was designed for high speed impact tests conducted at the Holloman High Speed Test Track. For this tool to be utilized by any other type of project or by any other organization the historical data imbedded in the tool would need to be modified.

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Vita

Laurie C. Knorr graduated from Howard High School in Ellicott City, Maryland. She then attended University of Maryland in College Park, Maryland. In June 2005, she graduated with a Bachelors of Science in Aerospace Engineering and a commission into the U.S. Air Force.

She spent 6 1/2 years as an acquisitions officer in the U.S. Air Force. Four of those years were spent working with directed energy and adaptive optics at the Starfire Optical Range in Kirtland AFB, New Mexico. More recently, she spent 2 1/2 years working with rocket propelled high speed sleds at the Holloman High Speed Test Track in Holloman AFB, New Mexico.

She is currently enjoying civilian life and looking forward to continuing to support systems engineering activities in her next job.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Leading Indicators (LI) were introduced to the Systems Engineering (SE) community in 2005. These measures are used to evaluate the effectiveness of how a specific work activity is applied on a project in a manner that provides information about impacts that are likely to affect the system performance. The LIs are designed to give a project manager/systems engineer insight into where their development project is heading and a chance to implement corrective actions early. This research strives to apply LIs to the testing community, specifically high speed sled testing, to improve the testing process and, in turn, improve the quality of the tests conducted. The thesis captures which SE processes are emphasized, valued and used in the high speed sled test community, then identifies LI trends that are most relevant to the high speed sled test community. Lastly, two of the top LIs - requirements maturity and requirements validation - were chosen for further trend analysis. Both of the LI trends were broken down into their suggested derived measures and current project trends were compared to historical trends.

15. SUBJECT TERMS

Leading Indicator; Systems Engineering; Defense Acquisition Guidebook; Systems Engineering Handbook; High Speed Sled Test; Sled Track;

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